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NASA TECHNICAL NOTE

NASA TN D-2991

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THERMOPHYSICAL PROPERTIES OF SIX CHARRING ABLATORS FROM 140° TO 700° K AND TWO CHARS FROM 800° TO 3000° K

R. Gale Wilson (Compiler)

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1965

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SUMMARY

Thermophysical property data of the type necessary for the performance analysis and design of entry heat-shields are presented for several ablation materials over the temperature range from -200° to 5000° F (144° to 3030° K). The data include enthalpy, specific heat, thermal conductivity, thermal expansion, density, and tensile and compressive mechanical properties of six ablation materials over the temperature range from -200° to 800° F (144° to 700° K). The enthalpy, specific heat, thermal conductivity, and total normal emittance of the chars formed from thermal degradation of two of the materials are also included. The char properties were measured over the temperature range from 1000° to 5000° F (810° to 3030° K). The materials studied are a high-density phenolic-nylon, a low-density phenolic-nylon, a filled silicone resin, the filled silicone resin in honeycomb, a carbon-fiber-reinforced phenolic, and a low-density filled epoxy in honeycomb. The first four materials were formulated and fabricated at the NASA Langley Research Center. The last two are commercially produced materials - Narmco 4028 and Avcoat 5026-39-HC G. The chars studied were produced from the high- and low-density phenolic-nylon materials.

The thermophysical property measurements were made under NASA contracts NAS1-2977 and NAS1-2978, with Melpar, Incorporated, and Southern Research Institute, respectively. Measurements on the low-density phenolic-nylon and the filled silicone resin were duplicated under the two contracts. The data obtained by the two independent firms are presented in graphical and tabular forms. The methods of measurement, the test apparatus, the procedures, and the composition and fabrication of the materials are described.

INTRODUCTION

Knowledge of certain basic physical properties of ablation materials and their temperature dependence is essential to the evaluation of their design and performance in entry heat-shield applications. The NASA Langley Research Center in June 1963 established a contractual program for the measurement of thermophysical properties of ablation materials. Specific heat, thermal conductivity, thermal expansion, density, emittance, and stress-strain data obtained during the period from June 1963 to January 1965 by Melpar, Incorporated (Contract Number NAS1-2977) and Southern Research Institute (Contract Number NAS1-2978)

are presented in this report. In addition, the report includes porosity data from measurements made at the NASA Langley Research Center to determine the pore-size and pore-volume distributions of the porous materials.

Six materials were evaluated (1) a high-density phenolic-nylon, (2) a low-density phenolic-nylon, (3) a filled silicone resin, (4) the filled silicone resin in honeycomb, (5) a carbon-fiber-reinforced phenolic, and (6) a low-density filled epoxy in honeycomb. The first four materials were formulated and fabricated at the NASA Langley Research Center. The last two are commercially produced materials, namely, Narmco 4028 and Avcoat 5026-39-HC G, in that order. All the aforementioned properties except emittance were determined for the six materials over the temperature range from -200° to 800° F (144° to 700° K). In addition, specific heat, thermal conductivity, and total normal emittance were measured for high- and low-density phenolic-nylon chars over the temperature range from 1000° to 5000° F (810° to 3030° K). Property measurements on the low-density phenolic-nylon and the filled silicone resin in the lower temperature range were duplicated on the two contracts, in order to ascertain the reliability of the data. All the data are presented in graphical and tabular forms, and the duplicate data are presented in a manner that facilitates comparison of the results obtained independently by the two investigating groups. The methods of measurement and the test apparatus employed are described in separate appendixes and/or referenced. The test procedures, the material compositions, and the methods of material fabrication are presented. For the convenience of the reader, a list of tables precedes the tables and a list of figures precedes the figures. The units for the physical quantities used in this report are given both in U.S. Customary Units and in the International System of Units (SI). Factors relating the two systems are given in reference 1 and appendix A.

The reader should be reminded that the properties of any material at a particular temperature can be defined uniquely only for thermal equilibrium or steady-state conditions. In view of the fact that ablation materials by the nature of their structure, composition, and application are unstable, it must be realized that thermophysical properties determined at temperatures in the thermal degradation zone are influenced by the time-dependent and temperature-dependent thermochemical reactions that occur. For all the materials studied in these efforts, excepting the chars, some thermal degradation begins at about 300° to 350° F (422° to 450° K), and at higher temperatures the data are, at best, a compromise. The thermal degradation process absorbs heat supplied to the material and thus prevents the achievement of steady-state or equilibrium conditions. The low thermal diffusivities of the materials add to the problem.

The duties of the compiler of this report included the responsibility for obtaining the porosity measurements as well as the establishment of the work requirements, technical monitoring of the contracts, and compilation of the other thermophysical data from contract work. Acknowledgment is made to Melpar, Inc., for the assistance of L. K. Eliason, D. H. Rice, E. L. Sanford, and T. L. Poe, and to Southern Research Institute for the assistance of C. D. Pears, G. F. Gillis, and C. M. Pyron, Jr.

DESCRIPTION OF ABLATION MATERIALS

Virgin Materials

High-density phenolic-nylon.- The high-density phenolic-nylon consisted of 50% by weight of Union Carbide "Bakelite" BRP-5549 phenolic resin, and 50% by weight of DuPont "Zytel" 103 nylon powder. The mixed materials were hot-pressed in a mold at a pressure of 700 psi (4.82 MN/m^2) while in vacuum and at a temperature of 320° F (433° K) for about 2 hours. The material was then cooled in the mold to room temperature with pressure and vacuum maintained. After removal from the mold, the material was postcured according to the following temperature cycle:

a. Start at 100° F (311° K), hold 1 hour

b. Raise temperature 10° F/hr (5.5° K/hr) to 200° F (366° K), hold 10 hours

c. Raise temperature 5° F/hr (2.8° K/hr) to 240° F (389° K), hold 10 hours

d. Raise temperature 5° F/hr (2.8° K/hr) to 300° F (422° K), hold 10 hours

e. Cool at 25° F/hr (14° K/hr) to 200° F (366° K), hold 4 hours

f. Cool to room temperature at 25° F/hr (14° K/hr)

Low-density phenolic-nylon.- The low-density phenolic-nylon consists of 25% by weight of Union Carbide "Bakelite" BRP-5549 phenolic resin, 25% by weight of Union Carbide phenolic Microballoons (BJO-0930), and 50% by weight of DuPont "Zytel" 103 nylon powder. The materials were purchased in the form of a ready-mixed molding compound.

The procedures for molding and postcuring the low-density phenolic-nylon were the same as those for the high-density phenolic-nylon except that the ram stops on the molding press were used to limit the molding pressure and thus achieve a predetermined and reproducible density of the molded material.

Filled silicone resin.- The filled silicone resin consists of 70% by weight of Dow Corning Sylgard 182 Resin, 14% by weight of Emerson and Cuming, Inc. SI grade Eccospheres, 9% by weight of Union Carbide phenolic Microballoons (BJO-0930), and 7% Sylgard 182 Curing Agent (catalyst). The Eccospheres and Microballoons were mixed by tumbling in vacuum at 210° F (372° K) for 2 hours to remove moisture and postcure the Microballoons. After the catalyst had been added to the resin, the already mixed Eccospheres and Microballoons were slowly added to the resin by manual mixing. The material was drawn into the mold under vacuum to remove entrapped air from the mixture. The molded blocks were cured at 140° F (333° K) at atmospheric pressure for about 12 hours.

Filled silicone resin in honeycomb.- The filled silicone resin in honeycomb is a composite of the filled silicone resin and phenolic-glass honeycomb with a nominal cell size of 1/4 inch (0.63 cm). The honeycomb is type HRP (GF11 cloth) of Hexcel Products, Inc. It has a nominal density of 3.5 lb/ft^3

($56\ kg/m^3$). The fabrication of this material differed from that of the preceding material only in that the honeycomb was mechanically forced into the filled silicone resin while the resin was still in the mold.

Carbon-fiber-reinforced phenolic.- The carbon-fiber-reinforced phenolic, containing approximately 50% by weight of 1/4-inch (0.63-cm)-long carbon fibers and 50% by weight of phenolic resin, was obtained from the Narmco Materials Division of the Whittaker Corporation in the form of a molding compound designated as Narmco 4028 and molded at the NASA Langley Research Center. The compound was hot-pressed at a pressure of 2000 psi ($13.79\ MN/m^2$) while in vacuum and at a temperature of 325° F (436° K) for 1.5 hours. The material was cooled in the mold to room temperature, with pressure and vacuum maintained. After removal from the mold, the material was postcured according to the following temperature cycle:

a. Start at 200° F (366° K), hold 4 hours

b. Raise the temperature 25° F/hr (14° K/hr) to 250° F (394° K), hold 4 hours

c. Raise the temperature 25° F/hr (14° K/hr) to 325° F (436° K), hold 4 hours

d. Cool at 40° F/hr (22° K/hr) to room temperature

Low-density filled epoxy in honeycomb.- The low-density filled epoxy in honeycomb was obtained from the Research and Advanced Development Division of Avco Corporation, and is commercially designated Avcoat 5026-39-HC G. The composition of the material is proprietary information.

Thermally Degraded Materials

High-density phenolic-nylon char.- The high-density phenolic-nylon char was produced by exposing 3-inch-diameter (7.6-cm) disks of the high-density phenolic-nylon to an electric-arc-heated subsonic stream of nitrogen for 210 seconds, the time required to produce a char layer of 1/4-inch (0.63-cm) thickness. The arc jet, described in reference 2, was operated with a nozzle 2 inches (5.1 cm) in diameter and with arc power of 1000 kilowatts. Under these conditions, the arc jet produced a thermal flux of about 100 Btu/ft^2-sec ($1.13\ MW/m^2$) on the phenolic-nylon disks located 2 inches (5.1 cm) from the nozzle, resulting in a maximum surface temperature of about 3000° F (1920° K). Stagnation pressure on the specimen was slightly greater than atmospheric pressure.

Low-density phenolic-nylon char.- The low-density phenolic-nylon char was produced by exposing 3-inch-diameter (7.62-cm) disks of the low-density phenolic-nylon material to an arc jet, in the same manner as that described for high-density phenolic-nylon char, except that the exposure time required to produce a 1/4-inch (0.63-cm) char layer was 120 seconds.

All the materials were supplied by NASA to the contractors in the form of blocks or disks; fabrication of the test specimens was part of the contract requirements.

APPARATUS, PROCEDURES, AND SPECIMENS

Details concerning the apparatus, test procedures, and test specimens related to each thermophysical property measurement are presented in appendixes B to G. In some cases, additional information is referenced. The appendixes are appropriately arranged to distinguish between the apparatus and methods of Melpar, Inc. and those of Southern Research Institute. The temperature range for which each method is applicable is also indicated.

In the work requirements for the thermophysical property measurements, the NASA originally requested specimen temperature-rise rates, where practicable, of at least 100° F/min (0.926° K/sec) between measurements above ambient temperature, with data at each test point to be obtained in the minimum time required to attain thermal equilibrium, or steady state, and to record appropriate data. Because of the low thermal diffusivity and high thermal reactivity of the ablation materials, and the incompatibility of some standard types of measurement apparatus with a 100° F/min (0.926° K/sec) rise rate, it was necessary in most cases to accept lower rates.

RESULTS AND DISCUSSION

Enthalpy and Specific Heat

Enthalpy and specific heat to 800° F (700° K).- Enthalpy and specific heat of the six ablation materials were determined by procedures and apparatus described in appendix B. A supplementary radiant-heating furnace was utilized by Southern Research Institute (SRI) to obtain rapid temperature-rise rates. These rates for the low-density phenolic-nylon were 120° F/min (1.11° K/s) near the outer surface and 75° F/min (0.69° K/s) at the center. For the filled silicone resin, the rise rate was 135° F/min (1.25° K/s) at the outer surface and 114° F/min (1.05° K/s) at the specimen center. Subsequent soaking times of 15 to 20 minutes in a furnace were required to establish equilibrium.

In the measurements by Melpar the temperature-rise rates were lower than those of SRI. The specimen was stabilized at the test temperature for 30 minutes to establish equilibrium.

The enthalpy data on all the materials are given in table 1. The specific heat data are presented in table 2. The enthalpy data on the high-density and low-density phenolic-nylon are presented in figures 1 and 2, respectively. The reference temperature for the Melpar data is 32° F (273° K) and that for the SRI data is 85° F (303° K). Hence, the enthalpy difference between the two curves in figure 2 at different temperatures should be constant. The

specific-heat curves, determined from the slopes of the enthalpy curves, are shown in figure 3. It can be seen that the Melpar and SRI data are in fair agreement except at the low and high ends of the temperature range. At -200° F (144° K), the percentage difference between the two sets of data is about 22 percent, and at 700° F (644° K) it is about 19 percent. Percentage difference here (and as used later in the report) is defined as the difference between the two sets of data divided by their average and multiplied by 100. It is of interest to note in figure 3 that the specific heats of high-density and low-density phenolic-nylon are experimentally identical, as would be expected from their identical basic composition.

Examination of weight-loss values in table 1 show that significant weight losses occurred at temperatures above 400° F (477° K). The enthalpy, at a given temperature was, in every case, calculated from the final weight of the specimen after test at that temperature.

The enthalpy data on the filled silicone resin and the filled silicone resin in honeycomb are given in figure 4, and the corresponding specific-heat data in figure 5. The enthalpy data obtained by Melpar for the filled silicone resin and the filled resin in honeycomb coincide, indicating that either the specific heat of the honeycomb itself is similar to that of the filled resin or that the relative volume of the honeycomb is too small for it to make an appreciable contribution to the enthalpy of the composite. The percentage difference between the Melpar and SRI enthalpy data on the filled silicone resin is about 33 percent at -200° F (144° K) and about 15 percent at 750° F (672° K).

The enthalpy curves for the carbon-fiber-reinforced phenolic and the low-density filled epoxy in honeycomb are presented in figures 6 and 7, respectively, and the corresponding specific-heat data are presented in figure 8.

Enthalpy and specific heat to 5000° F (3030° K).- The enthalpy and specific heat of the high- and low-density phenolic-nylon chars were determined by Southern Research Institute using a drop-type ice calorimeter which is described in appendix B. The enthalpy data are presented in table 1 and figures 9 and 10, and the corresponding specific-heat data are presented in table 2 and figures 11 and 12. The values of specific heat were obtained as the slopes of the enthalpy curves read at 1000° F (555° K) increments around mean temperatures and thus give the average specific heats at these mean temperatures. Since the enthalpy curves average out considerable scatter in the data at a given temperature, the specific heats are actually defined only within bands about the simplified curves shown in figures 11 and 12.

Thermal Conductivity

Thermal conductivity to 800° F (700° K).- Thermal conductivities of the six ablation materials were determined according to the procedures and techniques described in appendix C. The data of Melpar were obtained by using a radial-heat-flow technique requiring samples 1 inch (2.54 cm) in diameter and 1 inch (2.54 cm) long. The data of Southern Research Institute were obtained

on a guarded-hot-plate apparatus by using 3-inch-diameter (7.62-cm) disk specimens.

The conductivity data are presented in table 3 and figures 13 to 19. The data on high-density phenolic-nylon are contained in figure 13. A comparison between the Melpar and SRI data on low-density phenolic-nylon can be seen in figure 14. In the temperature region between -200° and -100° F (144° and 200° K), the percentage difference between the smoothed data of Melpar and those of SRI is 12 to 19 percent. The difference is about 35 percent at 200° F (366° K). However, scatter in the SRI data is about 23 percent of the value of the smoothed data at 200° F.

The data of Melpar and SRI on the filled silicone resin are shown together in figure 15. The agreement for this material is better than that for the low-density phenolic-nylon, but the percentage difference between the smoothed values is as much as 24 percent at 200° F (366° K). Data scatter is as much as 18 percent of smoothed values at this temperature. Both the Melpar and SRI data were obtained by proceeding from the lower temperature level to the next higher one with the same specimen, except that in some cases an individual specimen was used to obtain a single data point at the higher temperatures. The temperature-gradient ΔT data are presented in table 3 for SRI. The ΔT data from Melpar ranging from about 5° to 25° F (3° to 13° K) were generally lower than those from SRI except in the degradation-temperature region where they were as high as 180° F (355° K). However, the difference between values of ΔT does not provide a satisfactory explanation for the difference between the Melpar and SRI data, since the biggest difference occurs in the region where the conductivity is not changing rapidly with temperature.

The designations for the three characteristic directions of the honeycomb materials are shown in figure 16. The thermal-conductivity data for the filled silicone resin in honeycomb are presented in figure 17. The presence of the honeycomb makes a measurable difference in the conductivity for different directions; the conductivity is greatest in direction C, parallel to the honeycomb cells.

The thermal-conductivity data on the carbon-fiber-reinforced phenolic, and the filled epoxy in honeycomb are given in figures 18 and 19.

It should be pointed out that the actual weight losses due to degradation during the thermal-conductivity measurements were probably greater than those reported for corresponding temperatures in table 1 for the enthalpy measurements, because longer exposure times were required. Typically, 3 to 5 hours were necessary to stabilize at a particular temperature. In addition, the low conductivity of the materials in most cases resulted in hot-face temperatures considerably greater than the mean temperatures reported, with consequent thermal degradation greater than would be implied by the mean temperatures. Southern Research Institute estimated that thickness uncertainty due to thermal degradation in some cases resulted in possible errors in conductivity calculation of about ±7%, after corrections were made. Additional uncertainty resulted from excessive cracking of specimens at mean temperatures in excess of 700° F (644° K).

Thermal conductivity to 5000° F (3030° K).- A strip specimen configuration in conjunction with a radial-heat-flow apparatus was used to determine the conductivity of high-density and low-density phenolic-nylon char from about 1000° to 5000° F (810° to 3030° K). The apparatus is described in appendix C. The measurements were made in a helium environment at about 1 atmosphere (0.1 MN/m^2) pressure.

The thermal-conductivity data for the chars are presented in table 3 and figures 20 and 21. The rapidly changing slopes of the curves indicate that radiation is probably an important factor in the heat transfer.

It can be seen that the averaged conductivity of the high-density phenolic-nylon char (fig. 20) is somewhat lower than that of the low-density phenolic-nylon char (fig. 21). There is considerable scatter in the data for both materials.

Thermal Expansion

The apparatus and procedures applied in the measurement of thermal expansion of the six ablation materials to 800° F (700° K) are described in appendix D. Quartz-tube dilatometers were utilized in all the measurements.

The thermal-expansion data are presented in table 4 and in figures 22 to 29. The expansion curve for high-density phenolic-nylon is given in figure 22. The coefficient of expansion increases up to about 200° F (366° K) and is nearly constant from about 200° F to 400° F (478° K). The slopes which were used to calculate the coefficients of thermal expansion at the lower and upper ends of the curve are shown in the figure.

The thermal-expansion data of Melpar on the low-density phenolic-nylon are presented in figure 23 and those of SRI in figure 24. It can be seen that for the nearly linear region of the expansion curves from about -100° to 100° F (200° to 311° K) the coefficient of thermal expansion is about 30 μin/in-°F (50 μm/m-°K). The data of SRI show the expansion behavior of the material to be very erratic above 150° F (339° K). Above 400° F (478° K), thermal degradation precludes the acquisition of meaningful data; contraction, rather than expansion, occurs.

The thermal-expansion data of Melpar and SRI on the filled silicone resin are shown in figures 25 and 26, respectively. From about 0° to 300° F (255° to 422° K) the coefficient of expansion from the SRI curve is constant at about 70 μin/in-°F (130 μm/m-°K), and the Melpar curve has approximately the same slope in that temperature region. Erratic behavior of the material occurs above 400° F (478° K), as seen in figure 26, and rapid contraction occurs above 600° F (589° K). For both the low-density phenolic-nylon and the filled silicone resin, the percentage difference between the Melpar and SRI values for the coefficient of linear thermal expansion for the nearly linear regions of the expansion curves is no greater than 6 or 7 percent.

The thermal-expansion behavior of the filled silicone resin in honeycomb is shown in figure 27 for the directions A, B, and C (defined earlier in

fig. 16). The coefficients of expansion are given on the figure for the region of crossover of the curves (70° F (294° K)). It can be seen that the honeycomb orientation has an appreciable effect on the expansion behavior, except for the direction B, for which the expansion coefficient is about the same as that of the filled silicone resin itself (figs. 25 and 26).

The expansion data on carbon-fiber-reinforced phenolic are presented in figure 28. This expansion curve has a rather peculiar shape, with the slope varying from 9.4 to 220 μin/in-$^\circ$F (17 to 400 μm/m-$^\circ$K). The very steep slope around 500° F (533° K) is thought to be caused by a volume-expansion effect due to melting and flowing of the material at the outer surface of the specimen.

The expansion data for the filled epoxy in honeycomb are presented in figure 29. The honeycomb in this material has less influence on the thermal-expansion characteristics than the honeycomb in the filled silicone resin. For the temperature region from about -100° to 100° F (200° to 311° K), where the curves are nearly linear, the coefficient of linear expansion is about 18 μin/in-$^\circ$F (32 μm/m-$^\circ$K).

Emittance of Phenolic-Nylon Chars

The total normal emittances of the high-density and low-density phenolic-nylon chars were determined by a blackbody-comparison method which is described in appendix E. Since the exact test procedures were slightly different for the two chars, the emittance of each char will be discussed separately.

Emittance of high-density phenolic-nylon char.- The disks of char were impregnated with polyalphamethylstyrene to facilitate handling and machining. This resin began to vaporize at about 700° F (644° K) and was completely vaporized after about 15 minutes at 1000° F (810° K). By the prepositioning of the specimens in the apparatus, they were evaluated without subsequent handling after evaporation of the resin. Temperatures reported are optical pyrometer measurements. Thermocouple-temperature measurements were attempted and determined to be unreliable. Optical-pyrometer measurements were difficult to make because of nonuniformity in the temperature of the front surfaces of the specimens. The nonuniformity resulted from the char structure and the back-surface heating arrangement, which produced a temperature gradient through the specimen in the thickness direction.

A total of five specimens were fabricated and tested. The results are presented in table 5 and figure 30. During testing of specimen 1, which was 3/16 inch (0.48 cm) thick, there was some evidence of volume emission and possible transmission through the specimen as a result of its cellular structure. On subsequent specimens, a small amount of thermatomic carbon was carefully deposited in the surface cracks to reduce the subsurface emission. The emittance of the first specimen rose from about 0.70 at 1500° F (1088° K) to 0.87 at 2500° F (1643° K) and then decreased to 0.62 at 3300° F (2090° K).

Specimen 2 was approximately 1/8 inch (0.32 cm) thick. The tests were terminated after two test points because the subsurface emission appeared to be too severe.

Specimen 3 was also about 1/8 inch thick. The emittance decreased from 0.93 at 1700° F (1200° K) to 0.62 at 3400° F (2144° K).

For specimens 4 and 5, the thickness of the specimens was reduced to about 1/16 inch (0.16 cm) to permit higher temperatures. The emittance of specimen 4 rose from 0.77 at 1700° F (1200° K) to 0.89 at 3000° F (1922° K) and then decreased to about 0.80 at 4150° F (2560° K). The emittance of specimen 5 was nearly constant at about 0.75 over most of the temperature range from 1500° to 3900° F (1088° to 2423° K). It can be seen that there is a large scatter in the data between different specimens. This scatter may be attributed largely to the difficulties in measurement presented by the peculiar structure of the char. Using the mean of the tests, the emittance can be seen from the faired curve in figure 30 to fluctuate from about 0.75 to 0.85 over the temperature range from 1500° to 4150° F (1088° to 2560° K). At about 3400° F (2144° K), scatter in the data is about 37 percent of the mean value.

The assumption that the char is a graybody in behavior is discussed in appendix E as being an inherent part of the method of measuring emittance. Analysis using the data of reference 3 and the methods of reference 4 indicates that the total-emittance data may be about 10 percent high as a result of errors due to the graybody assumption.

Emittance of low-density phenolic-nylon char.- For the measurements of the emittance of the low-density phenolic-nylon char, no resin impregnant was used on the specimens because its vaporization from the unrestrained disk specimen tended to separate the cells of the char, allowing serious subsurface emission. It was found unnecessary to add thermatomic carbon to the cracks in this char because the subsurface emission and transmission of radiation were not as severe a problem as they were with the high-density phenolic-nylon char.

The total-normal-emittance data are presented in table 5 and in figure 31. There is somewhat better agreement between different specimens of this material than for the high-density char. The faired (mean) curve for the data for all the specimens lies between 0.85 and 0.93 except for the temperature range from about 2800° to 3400° F (1810° to 2144° K) in which the emittance drops to a minimum of about 0.70. This decrease was due to the formation of a white residue on the surfaces of the specimens within this temperature range. This formation was attributed to impurities in the specimens which vaporized at the higher subsurface temperatures and condensed on the cooler top surfaces of the specimens. That the impurities were in the specimen material rather than in the heating disks was assured by past experience with the heating disks, and by the fact that alternating the heating disks from tungsten to tantalum to graphite did not affect the emittance in this temperature range or cause any change in formation of the white residue. Above 3400° F (2144° K), the residue was not observed and the emittance returned to a value of about 0.9.

Measurements were not obtained at temperatures above 3900° F (2420° K) because back-face destruction of the material and melting of the heating disks occurred in attempts to obtain higher temperatures. The 3900° F (2420° K) temperature was obtained with a specimen of 1/8-inch (0.32-cm) thickness. Attempts to fabricate a thinner specimen failed because of the weak structure of the char.

Density

Bulk density of virgin materials.- The bulk densities for the six ablation materials as a function of temperature are reported in table 6 and figures 32 and 33. The determinations by Melpar were made from room-temperature measurements of density and calculations using the thermal-expansion data and the weight-loss measurements accompanying the enthalpy data. (See table 1.) Thus, the density data incorporate not only the effective decrease in density due to thermal expansion but also the effect of decreased weight at higher temperatures due to the loss of volatile products from thermochemical reaction.

The bulk-density data of SRI on low-density phenolic-nylon and the filled silicone resin were determined from room-temperature density and the thermal-expansion data. The density calculations were not made for temperatures in excess of 150° F (339° K) for the low-density phenolic-nylon and 400° F (478° K) for the filled silicone resin. Above these temperatures, the specimen-to-specimen variation in the thermal-expansion data and weight-loss data that are variable with exposure time were considered to make the calculations meaningless.

The difference between the Melpar and SRI data on the low-density phenolic-nylon and filled silicone resin is no greater than 1 percent.

Density of phenolic-nylon chars.- Measurements of true and apparent (bulk) densities at room temperature were made by SRI on the chars of both the high-density and low-density phenolic-nylon. Apparent density was determined by the standard technique of comparing the weights of a specimen in air and in water. Before immersion, the specimen surface was coated with a thin film of wax to prevent absorption of water, and the specimen was reweighed after immersion to assure that no water had been absorbed. The apparent densities for the high-density and low-density phenolic-nylon chars were 22.4 lb/ft^3 (360 kg/m^3) and 13.1 lb/ft^3 (210 kg/m^3), respectively.

The true densities were determined by grinding samples into fine powder and using a standard immersion technique for powders, equivalent to the ASTM D153-54 method (ref. 5). True density of high-density phenolic-nylon char was 91.7 lb/ft^3 (1.47 Mg/m^3) and that for the low-density phenolic-nylon char was 92.9 lb/ft^3 (1.49 Mg/m^3).

Porosity

Measurements were made at the NASA Langley Research Center to determine the distribution of pore sizes and pore volumes in the low-density phenolic-nylon, the filled silicone resin, the filled epoxy (excluding honeycomb), and the phenolic-nylon chars. Tests on the high-density phenolic-nylon and the carbon-fiber-reinforced phenolic indicated no open pores larger than 0.03 micron (0.03 μm). A mercury-intrusion method described in appendix F was employed to make the measurements. The measurements were treated to yield pore spectra, shown in bar-graph form in figures 34 to 38. Each of the bars represents a range of the pore diameters, given as the abscissa, and the volume of pores per

unit volume of material having the range of diameters is measured on the ordinate scale. Two specimens were evaluated for each material.

The method of measurement is designed to reveal open-pore characteristics of the materials. However, the data on the materials containing Microballoons and/or Eccospheres probably include the effects of the rupturing of some of these hollow spheres.

Some additional studies on porosities of the chars were made by Southern Research Institute. Total porosity was determined from the formula

$$P = \frac{\rho_t - \rho_a}{\rho_t} \times 100$$

where

P porosity, percent

ρ_t true density of the material

ρ_a apparent density of the material

The apparent porosity determined for high-density phenolic-nylon char was 75%, and that for the low-density phenolic-nylon char was 86%.

Photomicrographs of the chars were made on two planes, one parallel to and the other perpendicular to the thickness direction of the chars. The photomicrographs are shown in figure 39 and figure 40. The mean pore size was determined in a plane parallel to the thickness direction as the arithmetic mean of pore-size measurements obtained by traversing the magnified section with a calibrated eyepiece. The mean pore sizes for the high- and low-density phenolic-nylon chars were 24.2 microns (24.2 μm) and 7.9 microns (7.9 μm), respectively. It is apparent from the photomicrographs that the high-density phenolic-nylon char contains larger pore sizes and has a more discontinuous solid structure in planes perpendicular to the thickness direction than in planes parallel to the thickness direction.

Mechanical Properties

Tensile and compressive stress-strain data and associated mechanical properties were obtained on the six ablation materials, utilizing equipment which is described in appendix G. The mechanical properties of the materials are presented in tables 7 to 12 and in figures 41 to 85. These properties include Young's modulus, ultimate strength, yield strength at 0.2 percent offset, Poisson's ratio, and percent total elongation and compression.

Stress-strain data.- The tensile stress-strain curves for all the materials are presented in figures 41 to 50 and the compressive stress-strain curves, in

figures 51 to 62. In general, each stress-strain curve is an average curve for two tests.

In the Melpar tests, all loads were applied to the specimens with a crosshead rate of motion of 0.1 in/min (42 μm/s). In the SRI tests, the crosshead rate was constant for a given specimen, but it varied for different specimens from 0.009 to 0.050 in/min (4 to 21 μm/s) for the low-density phenolic-nylon in tension and compression. It varied from 0.007 to 0.100 in/min (3 to 42 μm/s) for the filled silicone resin in tension, and from 0.030 to 0.320 in/min (1 to 135 μm/s) for this material in compression.

In the temperature region from -200° to -100° F (144° to 200° K), Southern Research Institute experienced considerable difficulty in performing the tensile tests on the filled silicone resin because of its brittle behavior. In gripping the material, it was found that the normal gripping force inevitably resulted in specimen fractures in the grips. When the gripping force was reduced, the specimens generally slipped out of the grips prior to rupture. Finally, the tensile-specimen gage section was reduced to approximately 1/4-inch-square (0.63-cm) cross section, and the ends of the specimens were reinforced with epoxy. With this arrangement, gage fractures were obtained at -200° F.

Poisson's ratio.- Selected stress-strain data points, including lateral strain, are tabulated for the SRI evaluations in tables 8, 9, 11, and 12. Poisson's ratio which was calculated from these data is also shown in the same tables. Large variations in the values for Poisson's ratio from one temperature to another and the large scatter in values at a given temperature make the data appear to be of questionable value. Part of the measured motions at the higher temperatures can be attributed to shrinkage of the specimen as a result of thermal degradation.

Melpar also attempted to measure Poisson's ratio, and some values are reported in table 7 on the filled silicone resin and the carbon-fiber-reinforced phenolic. The behavior of the materials made it difficult to obtain meaningful data. In the case of the honeycomb composites, the cell walls acted as restraints that prevented the materials from behaving as homogeneous bulk material, and therefore made it impossible to obtain meaningful values for Poisson's ratio. In all cases, the specimens fractured along the irregular lines formed by the cell walls.

Young's modulus.- Young's modulus for tension and compression is shown for all the materials as a function of temperature in figures 63 to 73. There is considerable scatter in the data for a given temperature in many cases. The curves are drawn through the arithmetic mean of the set of values at each temperature. The scatter is generally greatest at temperatures below ambient temperature.

Comparisons between the Melpar and SRI data for Young's modulus on the low-density phenolic-nylon can be seen in figures 64 (tension) and 65 (compression). Between -100° and 400° F (200° to 478° K) the percentage difference between the tensile curves varies from 0 to 124%. At -200° F (144° K) the percentage difference is about 33%. The magnitude of scatter is about the same in each set

of data, being as high as about 47 percent at -200° F. For compression, poorest agreement is in the neighborhood of 200° F (366° K) and -200° F where the percentage differences are about 53 and 45%, respectively. The largest scatter in an individual set of data is about 32% at -100° F (200° K).

Comparisons between the Melpar and SRI data on Young's modulus on the filled silicone resin can be seen in figures 66 (tension) and 67 (compression). For tension, the best agreement is at ambient temperature, where the percentage difference between the curves is about 34%. The difference increases at higher temperatures to about 87% at 400° F (478° K) and increases at lower temperatures to about 173% at -100° F (200° K). Scatter is as much as 76% (SRI) at 0° F (255° K). For compression, the percentage difference between the curves is as much as 120% at -200° F (144° K). However, scatter in data (SRI) at this temperature is as much as 160%.

Ultimate strength.- Ultimate tensile and compressive strengths for all the materials as a function of temperature are presented in figures 74 to 85, using the same manner of presentation as that for the Young's modulus data. Agreement between the Melpar and SRI data for these properties is somewhat better than that for Young's modulus. The data for low-density phenolic-nylon are shown in figures 76 (tension) and 77 (compression). In figure 76, the greatest percentage difference between the two curves is 75% at 350° F (450° K). Scatter is as much as 48% (SRI) at -200° F (144° K). In figure 77 the highest percentage difference is 30% at 200° F (366° K). Scatter is as much as 35% (SRI) at -200° F.

The ultimate-strength data for the filled silicone resin are presented in figures 78 (tension) and 79 (compression). The percentage difference between the curves in figure 78 is a maximum of about 70% at 300° F (422° K). Maximum scatter is 30% (Melpar) at 400° F (478° K). The percentage difference between the curves in figure 79 is about 65% at -100° F (200° K) and 600° F (589° K). Scatter is as much as 90 percent (SRI) at -200° F (144° K).

In some of the Melpar tests, the limits of extension and compression measurements were about 4 and 7%, respectively. These limitations were imposed by the available travel of the recorder and by the measuring system. The limitations are indicated in the tables (tables 7 and 10). In such cases the ultimate strength is defined as the maximum stress. Generally, the ultimate strength in this report is defined as the maximum stress, but if the maximum stress occurred beyond 20% strain, the ultimate strength is defined as the stress at 20% strain.

In the course of machining tensile specimens of the filled silicone resin, Southern Research Institute observed that about 10% of the machined specimens had rather large voids visible on their surfaces and rejected them for testing. It seems quite likely that there may have been some hidden voids in this material which may have contributed to scatter in the mechanical-property data. Other factors to which data scatter may be related were those of brittle behavior at subzero temperatures and indications that moisture content may affect the properties in some cases. In view of the possible existence of variables associated with these observed phenomena and a greater number of uncertainties at degradation temperatures, perhaps the agreement between the Melpar and SRI

data is as good as could be expected. More precise definition of the mechanical properties would probably require a more exhaustive testing program exploring more variables and including a larger number of tests at each temperature.

CONCLUDING REMARKS

Thermophysical property data of the type necessary for the performance analysis and design of entry heat shields have been presented for six ablation materials. The measurements were made over temperature ranges from -200° to 800° F (144° to 700° K) on virgin ablation materials, and from 1000° to 5000° F (810° to 3030° K) on thermally degraded materials (chars).

The materials evaluated over the lower temperature range were a high-density phenolic-nylon, a low-density phenolic-nylon, a filled silicone resin, the filled silicone resin in honeycomb, a carbon-fiber-reinforced phenolic (Narmco 4028), and a low-density filled epoxy resin (Avcoat 5026-39-HC G). The properties determined for these materials were specific heat, thermal conductivity, linear thermal-expansion coefficient, density, and tensile and compressive stress-strain. In addition, porosity measurements were made at ambient temperature. The materials evaluated over the higher temperature range were two chars formed from thermal degradation of the high-density and low-density phenolic-nylon. The properties measured were specific heat, thermal conductivity and total normal emittance. In addition, density and porosity measurements were made at ambient temperature.

In an attempt to establish the reproducibility of the thermophysical properties, the results of two independent evaluations of the properties for the low-density phenolic-nylon and the filled silicone resin have been compared. This comparison reveals differences (as much as 170%) between the two sets of data too large to be reasonably attributed to cumulative errors in techniques of measurement. Scatter in a set of data (as much as 160%) in many cases comparable in magnitude with the difference between the sets of data also indicates erratic behavior of the materials that may be due to several variables in the thermal and environmental histories of the measurements. Physical variables such as voids within a material may be important factors in causing scatter in some cases. The percentage differences between the two independent sets of data and the scatter in each set of data are generally greatest at temperatures around and below -100° F (200° K) and above 300° F (422° K). Physical changes in the materials observed at cryogenic temperatures and physical and chemical changes accompanying the thermal degradation processes at temperatures above 300° F (422° K) appear to be primarily responsible for the largest variations in values of the thermophysical properties.

This compilation of thermophysical property data for several potential heat-shield materials, representative of the principal types of ablation materials presently being considered for thermal-protection applications, should provide considerable insight to the physical behavior of the materials over the practicable range of temperatures. It should also be useful data for analytical studies concerning theoretical ablation models. However, the user of the data

should be cognizant of the fact that thermophysical properties of ablation materials are not uniquely defined at temperatures which produce chemical or physical instability. It appears, from the property measurements reported here, that there are several variables which would have to be known and controlled in order to obtain data repeatable to within better than 25 to 175% for all the properties over the given ranges of temperatures.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., May 6, 1965.

APPENDIX A

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures, Paris, October 1960, in Resolution No. 12 (ref. 1). Conversion factors for the units used herein are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI unit
Temperature	$^{\circ}F$	$(^{\circ}F + 459.67)5/9$	degrees Kelvin ($^{\circ}K$)
Pressure	psi = lbf/in^2	6.895×10^3	newtons per square meter (N/m^2)
Temperature-rise rate	$^{\circ}F/hr$	5/9	degrees Kelvin per hour ($^{\circ}K/hr$)
Length	inch	0.0254	meters (m)
Density	lbm/ft^3	16.02	kilograms per cubic meter (kg/m^3)
Thermal flux	Btu/ft^2-sec	1.134×10^4	watts per square meter (W/m^2)
Temperature difference	$^{\circ}F$	5/9	degrees Kelvin ($^{\circ}K$)
Pressure	atmosphere	1.013×10^5	newtons per square meter (N/m^2)
Thermal expansion	$\mu in/in$-$^{\circ}F$	$9/5 \times 10^{-6}$	meters/meter-degrees Kelvin (m/m-$^{\circ}K$)
Length	micron	10^{-6}	meter (m)
Length-time ratio	in/min	4.233×10^{-4}	meters per second (m/s)
Calorimeter constant	$Btu/^{\circ}F$	1899	joules per degree Kelvin ($J/^{\circ}K$)
Force	lbf	4.448	newtons (N)
Heat capacity	Btu/lbm	2.324×10^3	joules per kilogram (J/kg)
Specific heat	Btu/lbm-$^{\circ}F$	4.184×10^3	joules/kilogram-degrees Kelvin (J/kg-$^{\circ}K$)
Thermal conductivity	Btu/ft-hr-$^{\circ}F$	1.730	watts/meter-degrees Kelvin (W/m-$^{\circ}K$)

*Multiply value given in U.S. Customary Unit by conversion factor to obtain equivalent value in SI unit.

Prefixes to indicate multiples of units are as follows:

Prefix	Multiple	Prefix	Multiple
giga (G)	10^9	centi (c)	10^{-2}
mega (M)	10^6	milli (m)	10^{-3}
kilo (k)	10^3	micro (μ)	10^{-6}

APPENDIX B

APPARATUS AND TEST PROCEDURE FOR MEASUREMENT OF SPECIFIC HEAT

Measurement of Specific Heat From -200° to 800° F (144° to 700° K)

Methods and apparatus (Melpar).- Specific-heat determinations at Melpar are made by means of a Bunsen ice calorimeter. The apparatus is designed to permit measurement of the enthalpy of materials over the temperature range from -320° to 1750° F (77° to 1230° K). From enthalpy measurements, the specific heat can be calculated.

A sketch of the ice calorimeter is shown in figure B1. The calorimeter consists principally of a double-wall pyrex vessel with dry CO_2 gas between the walls. The inner vessel (H) contains a mercury reservoir (K), outgassed distilled water (F) over the top of the pool of mercury, a hollow copper well (A) to receive the specimen, and an array of copper fins (J) which serve as the heat-exchange system for the copper well. The ice calorimeter measures the heat capacity of the sample by monitoring the volume change in a closed system of ice and water resulting from the heat exchange between the sample and the system.

In practice, the calorimeter is submerged in a 32° F (273° K) ice bath, and once thermal equilibrium is established, a mantle of ice is frozen around the fins. As ice freezes on the fins, mercury is expelled through a small capillary (E) to an external reservoir. When thermal equilibrium is reestablished, the expelled mercury is weighed. Then a heated specimen is dropped into the well, ice is melted, and mercury is drawn into the system from the external reservoir. When thermal equilibrium is again established, a measure of the amount of mercury drawn into the system provides for calculation of the heat content of the sample.

Specimens are heated by means of a platinum resistance furnace with a large silver core which serves to extend the length of the uniform-temperature zone. The copper well is extended out of the ice bath by means of a thin-wall monel tube which is connected by a vacuum seal to the furnace. The low conductivity of the monel tubing minimizes conductive heat leakage into the copper well. A gate prevents radiative heat transfer from the furnace to the calorimeter well. The initial specimen temperature is measured using a platinum/platinum—10-percent rhodium thermocouple at high temperatures and an iron-constantan thermocouple at low temperatures.

Temperatures below ambient are obtained by placing the specimen inside a liquid-nitrogen-cooled chamber which replaces the furnace above the calorimeter. Specimen temperatures intermediate between liquid-nitrogen temperature and ambient temperature are obtained by using the cooling chamber in conjunction with a small resistance heater wound around the sample container. For the measurements at temperatures below ambient, the freezing process is reversed - the

sample causes additional freezing on the mantle in the calorimeter and expels mercury from the system.

Specimens and procedure (Melpar).- Cylindrical specimens 0.5 inch (1.27 cm) in diameter and 1 inch (2.54 cm) in length are evaluated by the following procedure:

a. The ice calorimeter is brought to equilibrium with the ice bath at 32° F (273° K). This temperature is established to within $\pm 0.02^{\circ}$ F ($\pm 0.01^{\circ}$ K) to assure that any heat transfer will be adiabatic.

b. A mantle of ice is frozen on the fins of the calorimeter, and the system is allowed to attain equilibrium.

c. The amount of mercury in the external reservoir is weighed to an accuracy of 0.1 mg and the weight is recorded as M_1.

d. The test specimen is placed into a previously weighed container and the weight of the sample is determined to an accuracy of 0.1 mg.

e. The specimen container, with the sample inside, is suspended in the furnace (cooling chamber) and maintained at the desired test temperature for 30 minutes. During this time the furnace is purged with helium to provide good heat transfer into and out of the container.

f. The specimen container, with the specimen inside, is then allowed to fall freely into the calorimeter well and to remain there for 30 minutes to assure the establishment of equilibrium. During this time helium is forced to flow up the central well to reduce the collection of water vapor and to provide good heat transfer to the copper fins.

g. The weight of mercury in the external reservoir is again recorded as M_2.

h. The mercury-weight equivalence M_3 of the empty specimen container is determined at each specimen-test temperature. These measurements minimize errors due to radiative losses from the falling specimen container and also separate the portion of the heat exchange due to the container itself.

i. Periodically, a calibration test is made on a National Bureau of Standards Al_2O_3 calibration specimen over the range of representative temperatures. The calibration data are analyzed by using the data of reference 6. Thus, any errors in the heat transfer of the system are determined and applied as correction factors.

j. Enthalpy H of the test sample is calculated by the following equation:

$$H = \frac{\left(M_1 - M_2 - M_3\right)k}{M} = \frac{M_o k}{M} \tag{B1}$$

where

M_o mass of Hg displaced due to heat transfer from (to) the sample, lb (kg)

M_1 mass of Hg in external reservoir before specimen drop, lb (kg)

M_2 mass of Hg in external reservoir after specimen drop, lb (kg)

M_3 mass of Hg displaced due to heat transfer from (to) the sample container itself, lb (kg)

k calibration constant determined from tests on calibration specimen and NBS data on calibration specimen, Btu/lb (J/kg)

M mass of test specimen, lb (kg)

Because of the nature of the test method, the enthalpy of the sample is referenced to 32° F (273° K). The specific heat is determined as the slope of the enthalpy curve for small enthalpy and temperature changes.

Methods and apparatus (SRI).- Specific-heat measurements to 800° F (700° K) were made by using a dry-type adiabatic calorimeter which is described in considerable detail in reference 7. It is described briefly here.

The calorimeter consists principally of a covered brass cup, mounted on cork supports in a silver-plated copper jacket which is immersed in a bath of ethylene glycol. For measurements below ambient temperature, the bath is cooled by chilled trichloroethylene flowing through a copper cooling coil immersed in the bath. For measurements at temperatures above ambient the bath is heated by a nichrome wire heater. Uniform bath temperature is provided by a stirrer.

Copper-constantan thermocouples differentially connected between calorimeter cup and jacket indicate the temperature difference between the cup and the bath, allowing a difference of 0.03° F (0.02° K) to be detectable. During tests this difference is maintained to within 0.15° F (0.08° K). Absolute-temperature measurements of the cup are determined by series-connected thermocouple junctions located in wells in the bottom of the cup. All the thermocouple measurements are made by using a potentiometer in conjunction with a sensitive galvanometer.

A tubular furnace or a cold box is used to bring the specimens to the desired temperatures. By pivoting the equipment on a common post near the calorimeter, the specimen is transferred to a position directly over the calorimeter cup and is released by external triggering when the temperature has been stabilized. Adiabatic conditions are maintained during each test by manual adjustment of the cup guard-bath temperature.

A supplementary furnace is used to achieve rapid temperature-rise rates when desirable. The normally used furnace is purposely designed with a large mass to render it insensitive to minor variations in line voltage and air

currents. The supplementary furnace, mounted adjacent to the one normally used, provides rapid radiant heating of the specimen to within 15° F (8° K) to 20° F (11° K) of the desired test temperature. Then it can be rapidly transferred to the more massive preheated furnace for heat soaking to attain equilibrium.

Specimens and procedure (SRI).- Test specimens evaluated at temperatures above 300° F (422° K) are nominally 3/4-inch (1.9-cm) cubes. For measurements below 300° F the specimen size is varied to provide the specimen weight necessary to yield a change in calorimeter-cup temperature large enough to permit reliable evaluations.

A calorimeter constant, previously determined by using an electrolytic copper specimen of known specific heat, is used in the calculation of the enthalpy of the specimen. The enthalpy is determined as a function of the initial specimen temperature and then referred to an 85° F (303° K) base. The enthalpy of the specimen at any initial temperature is given by

$$H = \frac{K}{W_s}\left(T_2 - T_1\right) \tag{B2}$$

where

K calorimeter constant, 0.2654 Btu/°F (504.0 J/°K)

W_s specimen weight, lb (kg)

T_1 initial cup temperature, °F (°K)

T_2 final cup temperature, °F (°K)

The enthalpy is referred to the common base temperature of 85° F (303° K) by

$$H_{85} = \frac{H(T_2 - 85)}{T_3 - T_2} + H \tag{B3}$$

where

H_{85} enthalpy above the reference temperature of 85° F (303° K), Btu/lb (J/°K)

T_3 initial specimen temperature, °F (°K)

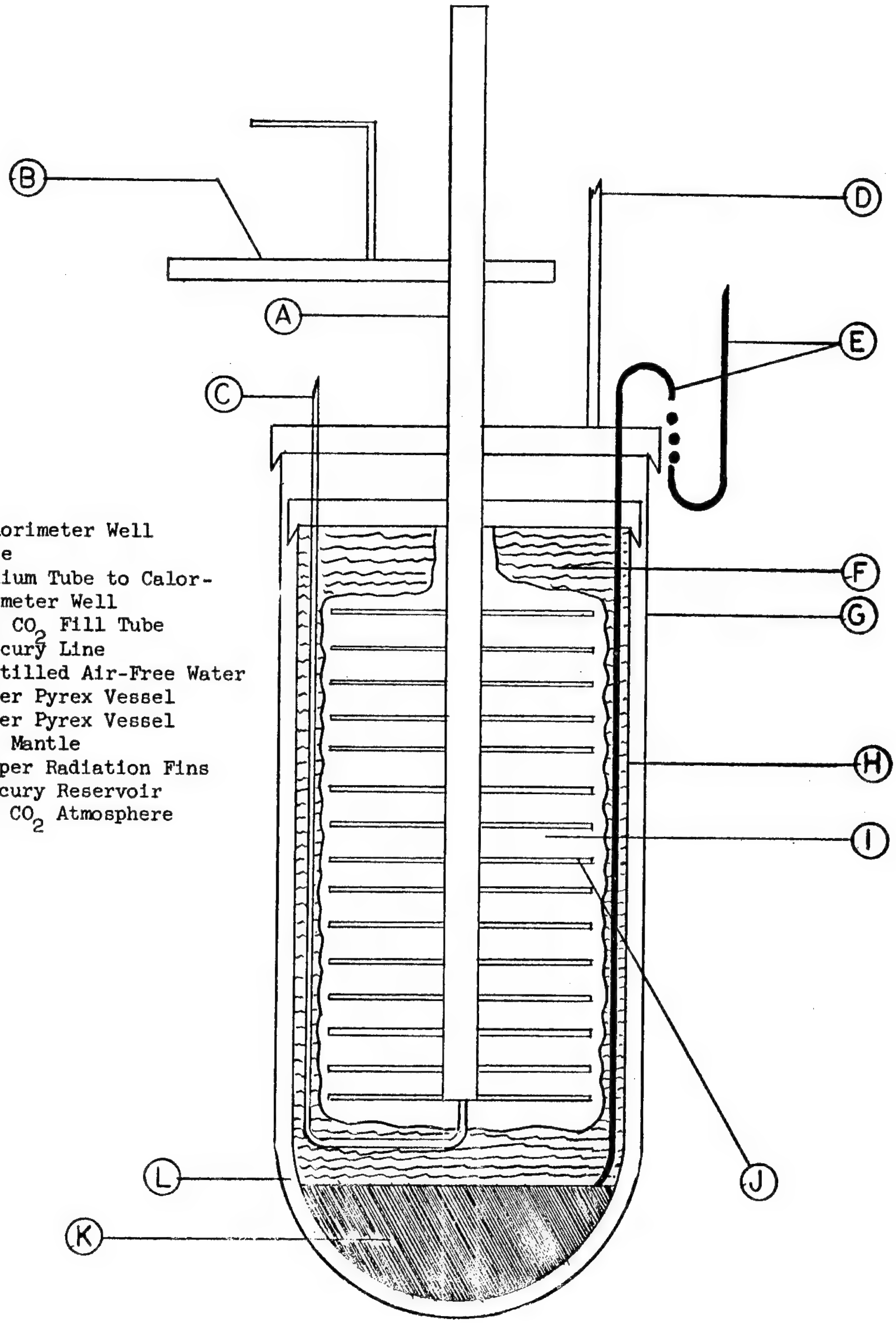
The reliability of the apparatus has been confirmed by making measurements on a sapphire specimen of known specific heat.

APPENDIX B

Specific Heat Measurements to 5000° F (3030° K) at SRI

Specific heat at temperatures from 1000° to 5000° F (810° to 3030° K) are determined using a drop-type ice calorimeter which is described briefly here and more completely in reference 8. The specimen is enclosed in a drop basket and heated by means of a thin-walled tubular resistance heater made from graphite. After the specimen is brought to the desired test temperature, it is dropped into an ice calorimeter in which the cup is surrounded by an ice mantle. As the ice melts, the volume change draws mercury from a calibrated manometer tube. The heat capacity of the specimen is determined from the mercury displacement. A flutter valve immediately above the calorimeter cup prevents radiation losses from the specimen up the drop tube. Helium, argon, or nitrogen environment can be used in the furnace.

Calibration for this apparatus is similar to that described for the Bunsen ice calorimeter of Melpar.



A - Calorimeter Well
B - Gate
C - Helium Tube to Calorimeter Well
D - Dry CO_2 Fill Tube
E - Mercury Line
F - Distilled Air-Free Water
G - Outer Pyrex Vessel
H - Inner Pyrex Vessel
I - Ice Mantle
J - Copper Radiation Fins
K - Mercury Reservoir
L - Dry CO_2 Atmosphere

Figure B1.- Bunsen ice calorimeter for measurement of heat capacity (Melpar).

APPENDIX C

APPARATUS AND TEST PROCEDURE FOR MEASUREMENT OF THERMAL CONDUCTIVITY

Measurement of Thermal Conductivity to 800° F (700° K)

Methods and apparatus (Melpar).- A radial-heat-flow technique is utilized in the measurement of thermal conductivity of thermally insulative materials. The temperature range extends from the temperature of liquid nitrogen to about 1100° F (866° K). The apparatus consists principally of a control heater for establishing a radial temperature gradient in the sample, heating and cooling environments for the sample, and the necessary electrical and temperature-measuring equipment associated with the radial-heat-flow technique.

The sample is heated from its center with a thin rod heater. Figure C1 shows a cross section of the apparatus. The center portion of the heater wire is provided with voltage taps so that the exact power over the center portion of the heater may be determined. The sample is provided with two thermocouples at different distances from the center of the sample, parallel to the central heater. An outer circumferential heater provides for heating the sample to make measurements at elevated temperatures.

For temperature measurements from slightly above ambient temperature down to -320° F (77° K), a cooling chamber surrounds the sample. This chamber consists of a material packing of high specific heat which is cooled to the desired temperatures by the repeated application of liquid nitrogen. The amount of insulating packing is varied in order to achieve various temperatures intermediate between ambient temperature and -320° F (77° K).

Specimens and procedure (Melpar).- The specimen is made up from five disks stacked together as shown in figure C1. Each disk is 1 inch (2.5 cm) in thickness and 1 inch in diameter. The central disk is the test specimen; the two disks on each end of it act as thermal guards to assure radial heat flow. Holes are machined through the centers of the disks to allow insertion of the central heater, and two holes are machined at radial distances r_1 and r_2 to permit placement of thermocouples to measure the radial temperature gradient. The temperatures at the two radial distances are measured by means of two calibrated iron-constantan thermocouples. An ice-bath reference junction is used.

When testing materials that exhibit asymmetric properties, the heat flow is measured separately along each principal axis of anisotropy.

For a typical thermal-conductivity determination, the procedure followed is given below:

a. The radial distances r_1 and r_2 are measured accurately before the stack is formed.

b. The five disk specimens, with the test specimen in the center are then stacked with the central heater along the central axis. The two calibrated thermocouples are placed through the thermocouple holes with their hot junctions resting in the central plane of the test specimen. The stack of disks is then wrapped in copper foil and inserted into the test chamber with the central 2-inch (5.08-cm) test length coinciding with the 2-inch constant-temperature zone in the test chamber.

c. Liquid nitrogen is introduced into the low-temperature chamber for the measurements below ambient temperature. After the specimen reaches thermal equilibrium with the cooling environment, the central heater is energized to produce the lowest desired steady-state temperature. By suitable monitoring of the liquid nitrogen, other temperatures below ambient are obtained. At each temperature, readings of voltage, amperage, and temperatures are recorded.

When the low-temperature measurements have been completed, the test specimen is examined for permanent shrinkage. If shrinkage has occurred, suitable corrections are introduced into the calculation of thermal conductivity. The specimen array is then reassembled and placed in the furnace, and measurements are made at temperatures above ambient, going from lower to higher temperatures.

d. As an alternate test method, the temperature chamber may be preset to a desired test temperature, the specimen package inserted into the chamber, and the central heater energized. The temperature gradient is then monitored until it becomes constant, at which time data are recorded.

Thermal conductivity K is calculated by the following equation:

$$K = \frac{Q \ln \frac{r_2}{r_1}}{2\pi L \Delta T} \qquad \text{(C1)}$$

where

Q rate of heat flow to test zone, Btu/hr (watts)

ΔT temperature difference between r_1 and r_2, $^\circ$F ($^\circ$K)

L length of the test zone, ft (m)

<u>Test methods and apparatus (SRI)</u>.- Thermal-conductivity measurements to 1000° F (811° K) are made with a guarded hot plate which is a slight modification of the standard ASTM C177-63 design (ref. 9). This apparatus is described briefly here and more completely as the 3-inch (7.6-cm) apparatus in reference 7. The apparatus consists principally of a central heater plate surrounded by a guard heater, each separately controlled. The guard heater is maintained at the same temperature as the central heater to assure that all heat flow is normal to the specimen surfaces. The temperature difference between the guard and central sections is monitored by means of series-connected

differential thermocouple junctions. The plate containing the central and guard heaters is sandwiched between layers of sheet insulation, the hot-face thermocouples, the specimen, cold-face thermocouples, more sheet insulation, copper plates, and finally, cold sinks to dissipate the heat. In addition to the thermocouples in contact with the specimen, thermocouples are located in the central heater and in the outer copper plates to monitor their temperatures. The thermocouple measurements are made by using a potentiometer in conjunction with a sensitive galvanometer.

The assembly is arranged to operate with the specimen placed in the apparatus horizontally. In order to maintain good contact pressure, a screw-loading device holds the sandwich assembly together.

To obtain mean sample temperatures above ambient temperature, water is circulated through the copper tubing of the heat sink. For mean sample temperatures below ambient temperature, liquid nitrogen vapors are circulated through the copper tubing.

The thermal conductivity K is calculated from the following equation:

$$K = \frac{QX}{A\Delta T} \tag{C2}$$

where

Q rate of heat flow, Btu/hr (watts)

X average thickness of specimen, in. (cm)

A area of central-heater section, ft^2 (m^2)

ΔT sum of temperature gradients across the two samples, $^{\circ}F$ ($^{\circ}K$)

Theoretically, the heat input Q should divide, with half the input flowing through each sample. In practice this exact division rarely occurs; instead, there is a slight unbalance in the heat flow. Equation (C2) then permits a calculation of the arithmetic average for the two samples.

Thermal Conductivity to 5000° F (3030° K)

Test methods and apparatus.- The method applied by Southern Research Institute in obtaining thermal-conductivity data on chars to 5000° F (3030° K) is a modified radial-heat-flow technique which was developed primarily for determination of the conductivity of pyrolytic graphite in the "A" and "C" directions. The apparatus consists of a high-temperature furnace which surrounds the specimen assembly, a radial-heat-flow assembly that includes a water calorimeter, and temperature-measurement apparatus.

APPENDIX C

The furnace provides an isothermal hot zone no less than 4.75 inches (12.1-cm) long, with at least a 3 to 1 ratio of the length of the hot zone to that of the furnace. The furnace is designed to withstand temperatures up to 5600° F (3370° K) and to provide inert-atmosphere protection for the specimen and graphite components of the furnace. The furnace contains ports that provide for thermocouple or optical temperature measurements at selected points in the specimen.

A schematic of the specimen configuration used in making conductivity measurements is shown in figure C2 and the specimen dimensions are shown in figure C3. Since pyrolytic graphite has a thermal-conductivity value for the "A" direction of about 200 times that for direction "C" at 500° F (532° K) and about 60 times that for direction "C" at 3500° F (2200° K), the strips of this material (see fig. B3) assure an evenly distributed flow of heat across the faces of the specimens.

Prior to the machining of the specimens, the char was impregnated with polyalphamethylstyrene to provide mechanical stability. A sample was weighed before the impregnation, after the impregnation, and after a 15-minute heat soak at 1000° F (810° K) to determine if the impregnant had fully vaporized. These evaluations verified that no measurable residue was left.

The water calorimeter (see fig. C2) passes axially through the specimen assembly and provides a heat sink to create an axial temperature gradient. In addition, it provides for measurement of the absolute value of the heat flow for a 0.5-inch (1.27-cm) gage section of the specimen. This measurement is determined from thermocouples mounted 0.5 inch apart in the calorimeter water stream to determine the temperature rise of the water due to the flow of heat through the gage section of the specimen.

Calculations.- The heat flow through the 0.5-inch (1.27-cm) gage length of the specimen assembly is obtained from the following equation:

$$Q = Mc\Delta T_c \tag{C3}$$

where

Q rate of heat flow, Btu/hr (watts)

M rate of water flow, lb/hr (kg/s)

c specific heat of water, Btu/lb-°F (J/kg-°K)

ΔT_c temperature difference between the two thermocouples inside the calorimeter tube, °F (°K)

The thermal conductivity K of the char is calculated from the following equation:

$$K = \frac{QL}{A\Delta T_s} \tag{C4}$$

where

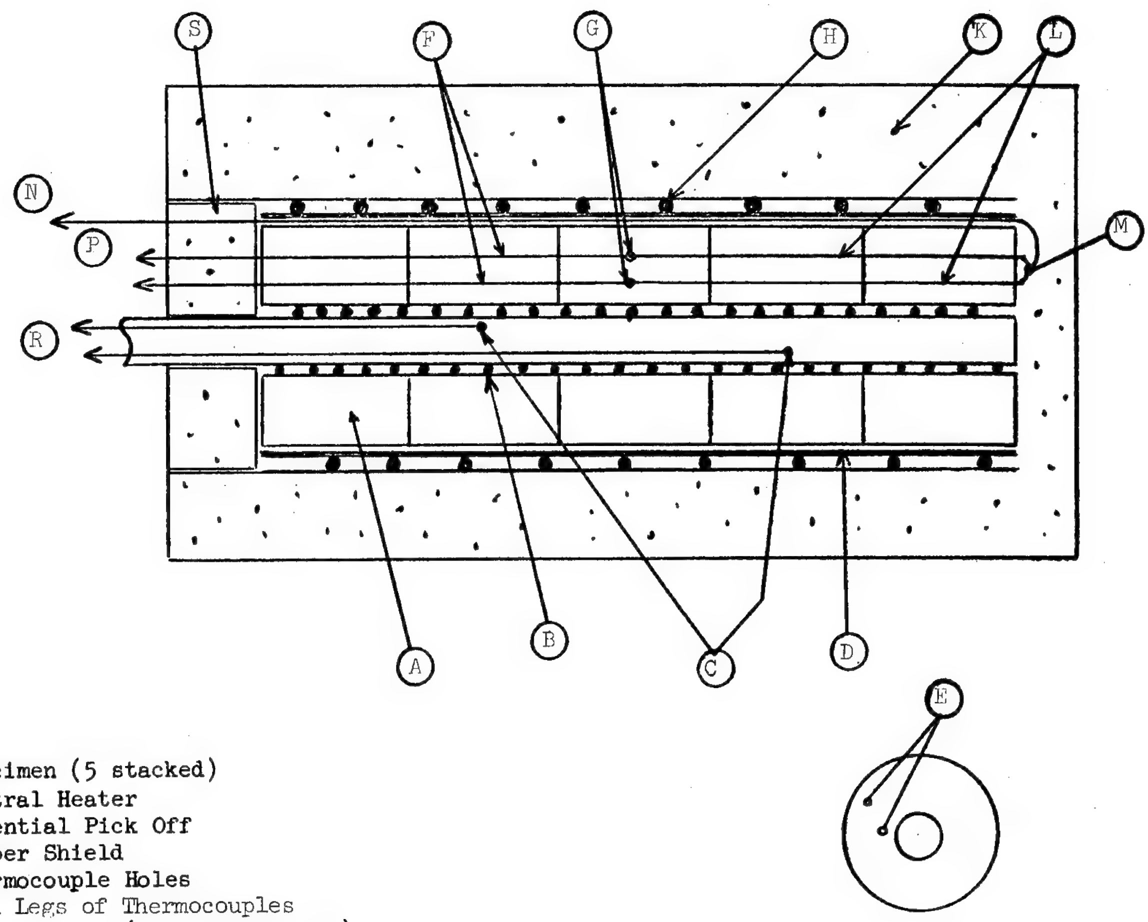
L distance over which ΔT_s is measured, ft (cm)

A area through which Q is flowing, $ft^2(m^2)$

ΔT_s temperature difference between the two temperature-measurement cavities in the specimen, $^{\circ}F$ ($^{\circ}K$)

For temperatures below 2000° F (1365° K), ΔT_s was measured with thermocouples, and the specimen mean temperature was determined as the arithmetic average of the outer and inner thermocouples. For temperatures above 2000° F, measurements were made with an optical pyrometer by sighting through a right-angle mirror device into the temperature-measurement cavities, shown in figures C2 and C3. Due to radiation losses resulting from the large ratio of depth to diameter of these cavities, the observed temperatures were lower than the actual temperatures of the corresponding isothermal planes of the specimen. However, unless ΔT_s was very large, the error was about the same for each cavity, and therefore ΔT_s could be measured quite accurately as the difference between the two observed values. Then by assuming that the temperature gradient through the specimen material was linear (see fig. C4), the mean temperature could be calculated from a true outer-face temperature measurement (through a furnace port) and a knowledge of the locations of the temperature-measurement cavities in the specimen. The calculation of mean temperature (fig. C4) is based on the properties of similar triangles where the vertical legs of the triangles represent temperature differences and the horizontal legs represent distances between points of measurement. For simplification, both temperature-measurement cavities are shown in one strip of the specimen, whereas they actually are in two strips located in opposite positions in the specimen assembly (see fig. C2).

APPENDIX C



A - Specimen (5 stacked)
B - Central Heater
C - Potential Pick Off
D - Copper Shield
E - Thermocouple Holes
F - Iron Legs of Thermocouples
G - Thermocouples (Iron-Constantan)
H - Heater
K - Insulation
L - Constantan Legs of Thermocouples
M - Weld Joint for Constantan Legs
N - Common Constantan Lead
P - Iron Leads
R - Potential Leads
S - Plug

Figure C1.- Cross section of radial heat-flow thermal-conductivity apparatus (Melpar).

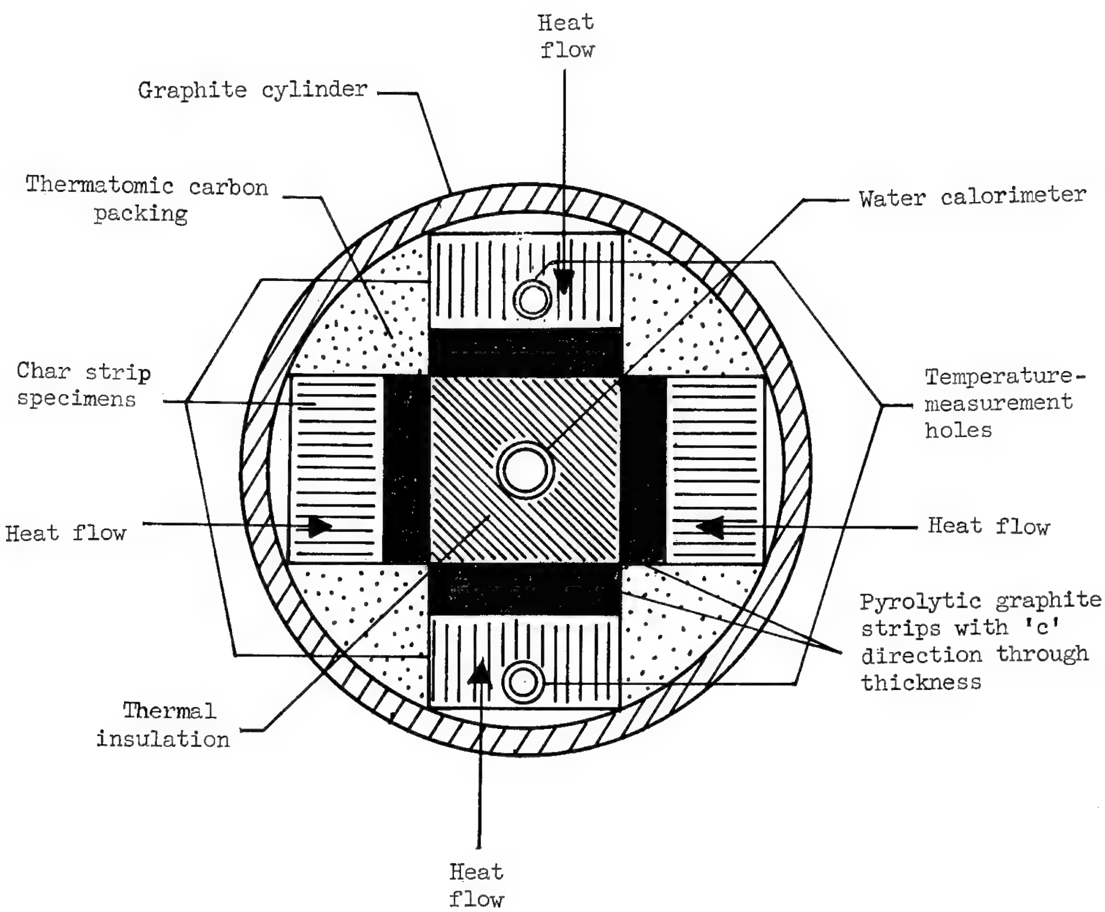


Figure C2.- Strip-specimen configuration for thermal-conductivity measurements (SRI).

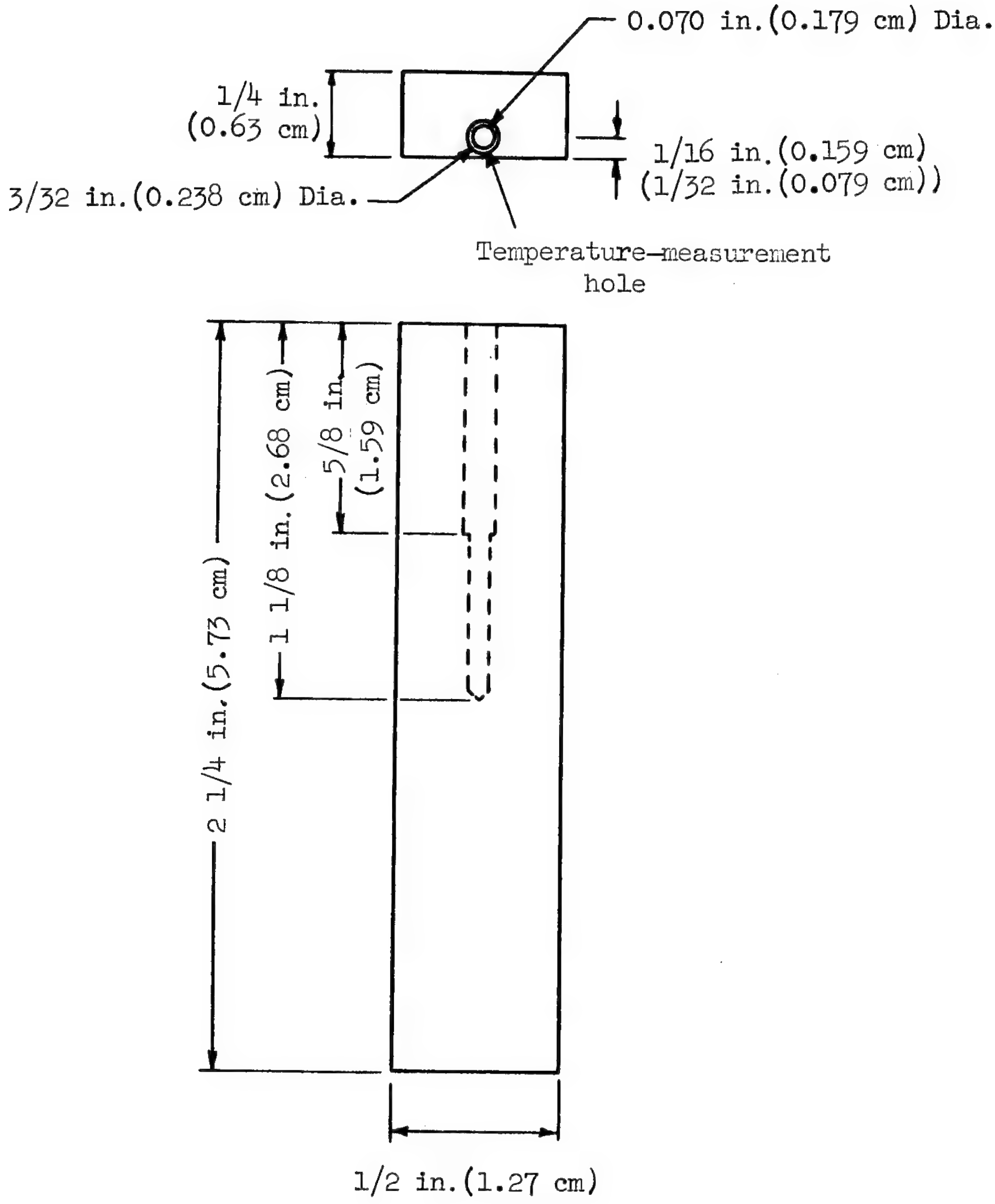
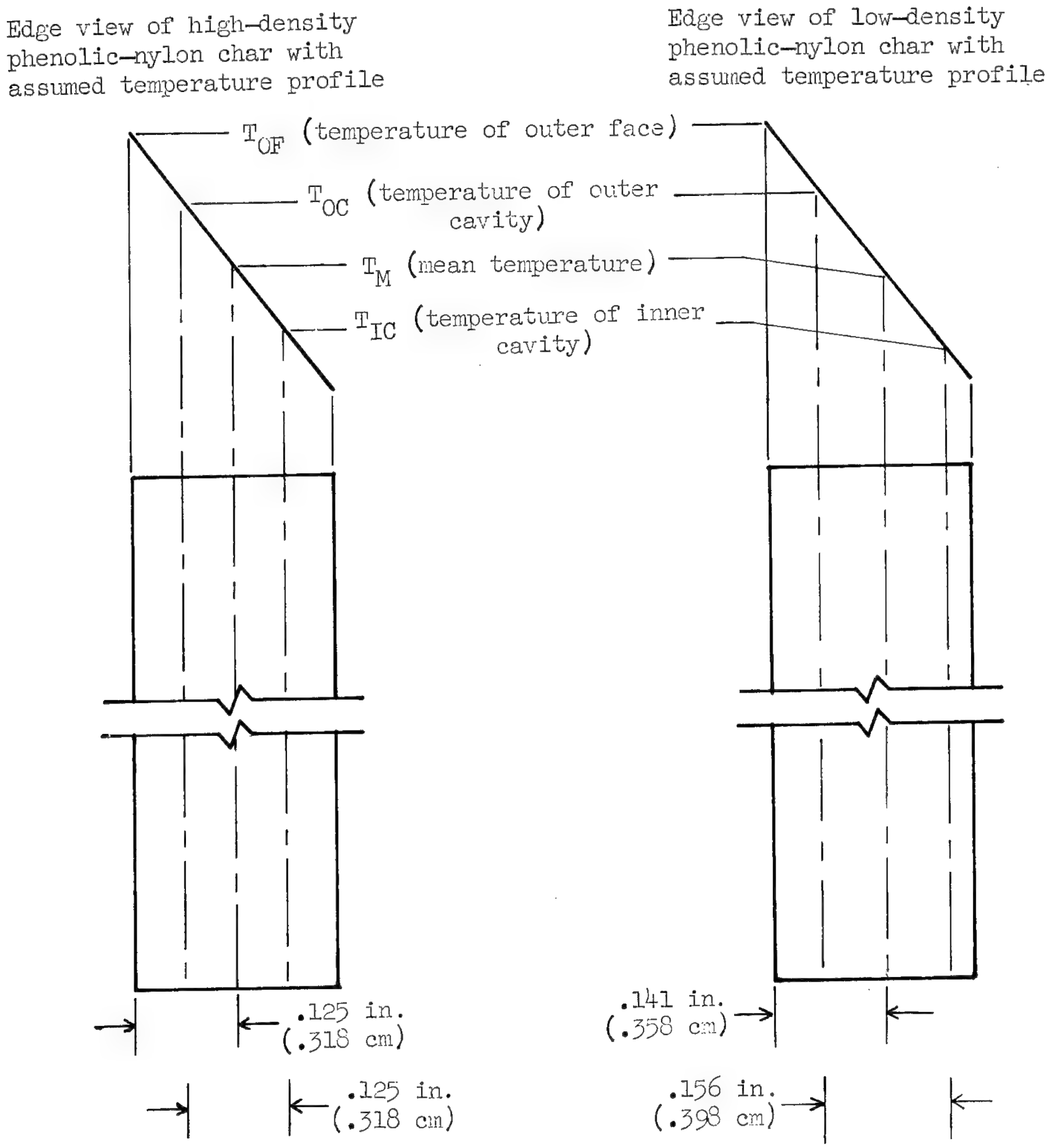


Figure C3.- Sketch of thermal-conductivity strip specimen (SRI).



$$\frac{T_{OF} - T_M}{.125} = \frac{T_{OC} - T_{IC}}{.125}$$

$$T_M = T_{OF} - (T_{OC} - T_{IC})$$

$$= T_{OF} - \Delta T_S$$

$$\frac{T_{OF} - T_M}{.141} = \frac{T_{OC} - T_{IC}}{.156}$$

$$T_M = T_{OF} - 0.9\,(T_{OC} - T_{IC})$$

$$= T_{OF} - 0.9\,\Delta T_S$$

Figure C4.- Determination of mean temperature for chars (SRI).

APPENDIX D

APPARATUS AND TEST PROCEDURE FOR MEASUREMENT OF THERMAL EXPANSION

Thermal Expansion to 800° F (700° K)

Methods and apparatus (Melpar).- The coefficient of linear thermal expansion of materials at temperatures between -320° F (77° K) and 2200° F (1478° K) is determined at Melpar by using a quartz dilatometer. A schematic of the apparatus is shown in figure D1. Any expansion or contraction of the specimen (R) is transferred to the dial indicator (M) by the fused quartz tube (P) which has closed ends. The dial indicator is capable of showing a change in sample length of 0.0001 inch (2.5 μm). The dial gage exerts a pressure no greater than ±10 psi (69 kN/m^2) upon the specimen.

Shown on the left side of figure D1 is a schematic of the temperature chamber which provides for heating or cooling the sample. A 3-inch (7.6-cm) zone within the chamber is designed to be uniform to within ±2° F (±1° K) from the center to either the top or bottom. A control thermocouple is provided at the center of the test zone to monitor the test temperature.

Specimens and procedure (Melpar).- The specimen length ranges from 2 to 3 inches (5 to 8 cm) depending upon the expansion characteristics of the material under test. The ends of the specimen are cut perpendicular to the axis of the specimen. The procedure for a typical test is as follows:

a. The length of the sample is accurately determined at room temperature.

b. The specimen is inserted into the dilatometer, and a thermocouple is mounted in the assembly with its hot junction against the center of the sample. The entire assembly is inspected to assure freedom of movement of both the inner quartz transmission tube and the dial indicator. The dial indicator is adjusted to zero.

c. The quartz dilatometer with specimen is placed into the temperature chamber.

d. Testing is started with the low-temperature range first. Liquid nitrogen is introduced into the cooling jacket, and the sample attains liquid-nitrogen temperature. The differential expansion ΔL is recorded. The sample temperature is then increased to the next desired value by energizing the heater and establishing a new state of equilibrium. The differential expansion is recorded at the new temperature. This process is repeated until the sample temperature has returned to room temperature.

If the sample length has not returned to its initial value, it is replaced by a new sample before measurements are made at higher temperatures. For measurements at temperatures above ambient, the sample is heated to each temperature in an ascending sequence. If it is anticipated that the material under

study will exhibit hysteresis in expansion characteristics, the test sequence is reversed, going from the highest temperature to lower temperatures.

e. As an alternate test method, the temperature chamber may be preset at a desired test temperature and the dilatometer may be inserted into the chamber at this temperature. The sample temperature then may be monitored and the differential expansion recorded upon the attainment of equilibrium conditions.

The coefficient of linear thermal expansion α is calculated from the following equation:

$$\alpha = \frac{\Delta L}{L(T - T_O)} + \alpha_{qt} \tag{D1}$$

where

ΔL differential change in length of specimen and quartz outer tube at test temperature T, in. (m)

L initial length of test specimen at room temperature, in. (m)

T test temperature, $^{\circ}F$ ($^{\circ}K$)

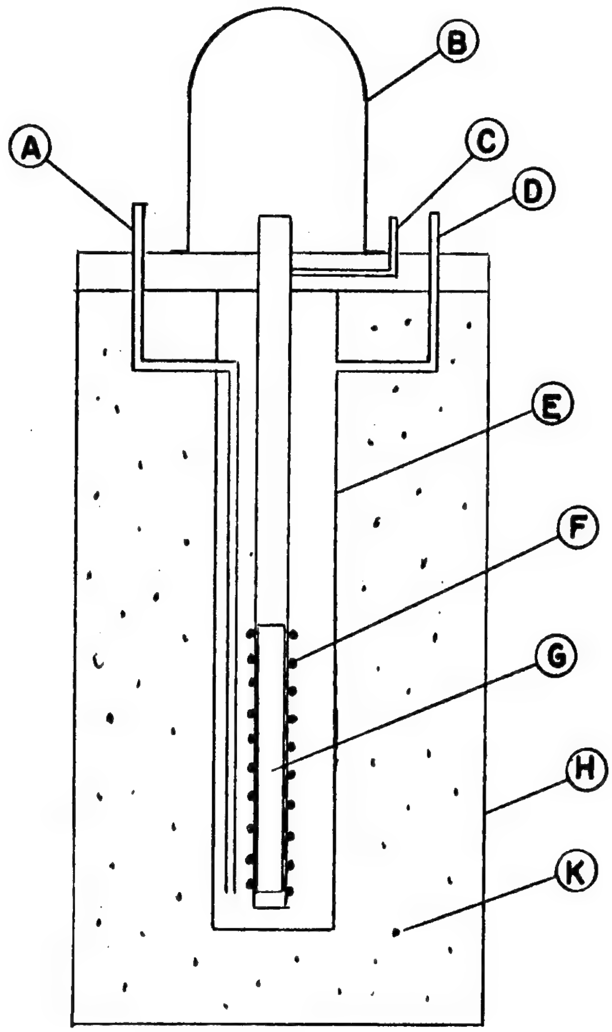
T_O ambient temperature, $^{\circ}F$ ($^{\circ}K$)

α_{qt} linear coefficient of thermal expansion of quartz outer tube at test temperature T

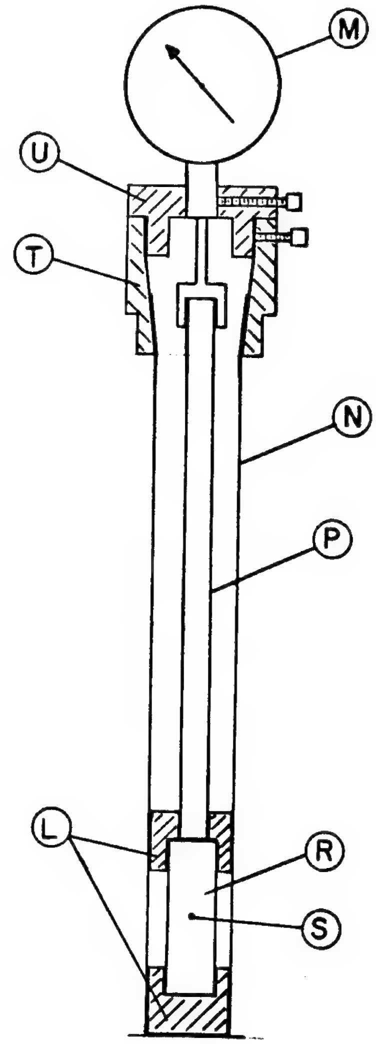
Apparatus and test procedure.- Thermal-expansion measurements to 1000° F (811° K) are made at SRI by utilizing quartz-tube dilatometers. The apparatus is described only briefly here. It is described in more detail in reference 7. The tubes and dial gages are mounted on a single arm to facilitate the testing of two samples simultaneously. The dial gages are graduated in 0.0001-inch (2.5-μm) divisions with a total range of 0.100 inch (2.5 mm) for specimens with low coefficients of expansion, and 0.500 inch (1.27 cm) for specimens with higher coefficients.

For measurements above ambient temperature, each dilatometer is heated by an individual heater. For measurements below ambient temperature the dilatometers are cooled by a Dewar flask filled with dry ice and trichloroethylene. The dilatometer tubes are submerged in the flask to a depth sufficient to cover the specimens. Iron-constantan thermocouples are placed at each end and at the center of each specimen to monitor the temperature throughout the specimens. The specimens are nominally 3 inches (7.6 cm) in length with the ends rounded on a 3-inch (7.6-cm) diameter.

The reliability of the apparatus has been checked by making measurements on nickel, quartz, and graphite to compare with values in the literature. Good agreement was found between values measured with this apparatus and those reported in the literature.



FURNACE



DILATOMETER

Legend

A – Liquid-nitrogen inlet
B – Bell jar
C – Vacuum port
D – Air vent
E – Metal dewar
F – Heater winding
G – Copper can
H – Metal housing
K – Insulation

L – Sample aliner (quartz)
M – Dial indicator
N – Quartz tube
P – Quartz tube
R – Specimen
S – Thermocouple
T – Invar dial-gauge holder
U – Invar quartz-tube holder

Figure D1.- Apparatus for measurement of thermal expansion (Melpar).

APPENDIX E

APPARATUS AND TEST PROCEDURE FOR MEASUREMENT OF EMITTANCE

The apparatus and methods used by Southern Research Institute to measure total normal emittance are described in detail in reference 8. They are described briefly below.

Emittance is measured by comparing the energy received by a radiometer from the sample to that received from a blackbody cavity maintained at the same temperature. The equipment consists principally of an induction heating furnace, a radiometer, and temperature-measurement equipment. A cross section of the apparatus is shown in figure E1. The specimen (1) is supported in the center of a flat concentrator induction coil (2) by a zirconia cylinder filled with fine zirconia grog and tungsten wires (3). The zirconia cylinder rests on a cylinder filled with coarse zirconia grog (4). The radiometer (5) views the specimen from directly above through a water-cooled tube (6). A water-cooled valve (7) is used to blank off the specimen from the radiometer. Optical-temperature readings are taken through the main port (8), which may be pushed in to allow viewing of the specimen by way of a right-angle mirror (9). When radiometer readings are being taken, the port is pulled out of the line of sight. Direct viewing of the specimen is permitted by an auxiliary port (10). The portion of the furnace (11) above the specimen is water cooled to eliminate the reradiation of energy back onto the specimen surface. The furnace is capable of maintaining a vacuum.

The radiometer is calibrated for blackbody radiation by using a graphite cavity with a 6 to 1 aspect ratio. The temperature of the cavity is determined by thermocouples in the bottom of and within the cavity and by optical-pyrometer measurements.

The geometry of the sample is that of a disk 1/2 inch (1.27 cm) in diameter and 3/16- to 1/8-inch (0.48- to 0.32-cm) thick. The sample is placed on the surface provided by the zirconia cylinder, grog, and tungsten wires. The radiometer observes an area of slightly less than 1/4 inch (0.63 cm) in diameter. If the sample material cannot be inductively heated, tungsten and tantalum heating disks are placed under the specimen. During a test the furnace is purged with argon. The temperature of the specimen is monitored by thermocouples located directly on the specimen surface and by optical-pyrometer readings. The optical-temperature readings must be corrected to obtain true temperatures. These corrections are for emittance and for absorption by the sapphire windows of the ports and by the mirror.

The correction for emittance is determined by an iterative process in which an arbitrary initial total-emittance value is assumed for determining a first-order "true" temperature. The ratio of the observed specimen radiometer output to the blackbody output for this temperature is calculated as the first-order value of the emittance at that temperature. If the assumed emittance is correct, the calculated value will agree with it; if not, the calculated value

is used to replace the former assumed value and the process is repeated until the assumed emittance value agrees with the calculated value. The iterative process will converge on the correct emittance value if it is valid to assume that the thermal energy at the particular temperature has a graybody distribution. In other words, it must be assumed that the total emittance is equal to the spectral emittance at the wavelength of the pyrometer. The error in emittance values determined for nongray materials will vary, depending on the difference between the spectral normal emittance at the pyrometer wavelength of 0.665 micron (0.665 μm) and the total normal emittance.

APPENDIX E

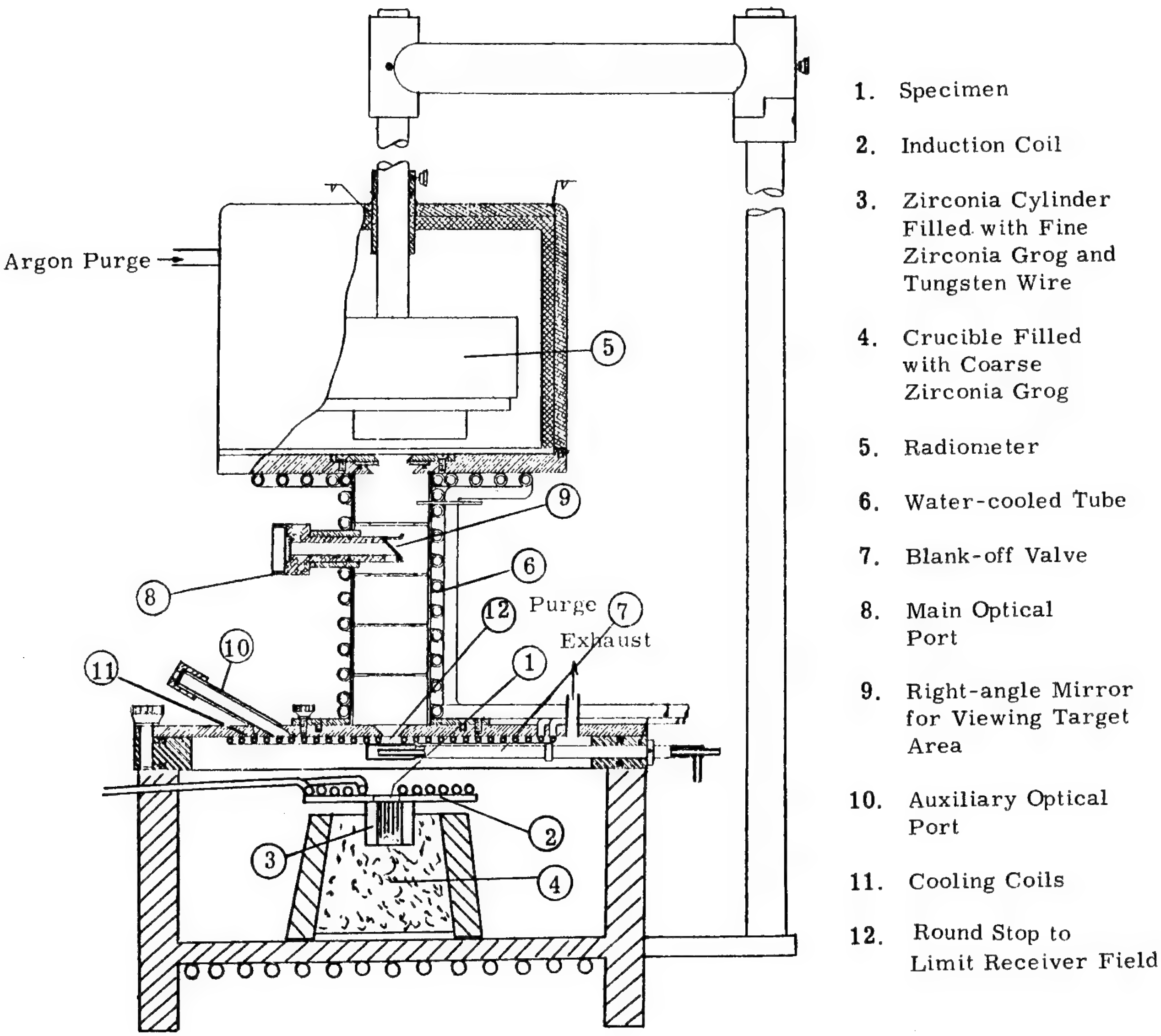


Figure E1.- Cross section of apparatus for measurement of total normal emittance (SRI).

APPENDIX F

APPARATUS AND TEST PROCEDURE FOR MEASUREMENT OF PORE-SIZE DISTRIBUTION

Pore-size distributions for the ablation materials were determined by a mercury-intrusion method which is described in detail in reference 10. It is described briefly here.

The basis of a liquid-intrusion method of measuring pore sizes and volumes is the nonwetting characteristic of the liquid used. Pressure is required to force the liquid to enter the pores, and the pressure increases as the pore size decreases. The pressure required is determined by the surface tension of the liquid, the contact angle, and the diameter of the smallest pore filled at the given pressure.

The experimental apparatus is designed to force mercury into the pores of a material at pressures ranging from subatmospheric to 5000 psi (35 MN/m^2) and simultaneously to indicate the volume of mercury absorbed at a given pressure, permitting the determination of pore sizes and pore volumes for pore diameters ranging from 100 to 0.03 microns (0.03 μm). The volume penetration of mercury into a specimen is measured by a calibrated glass stem which is a part of the sample container (penetrometer) and through which the mercury passes as it enters the specimen; pressure is recorded simultaneously.

For measurement of the pore sizes ranging from about 100 to 20 microns (100 to 20 μm), the penetrometer and sample are evacuated, and the pressure is increased by increments to force mercury into the pores until the pressure reaches 1 atmosphere (0.1 MN/m^2). Then for measurement of pore sizes from about 20 to 0.03 microns (20 to 0.03 μm), the penetrometer is inserted into a hydraulic pressure vessel where the pressure can be increased in any desired increments from 1 atmosphere to 5000 psi (35 MN/m^2). A window in the pressure vessel allows continued reading of the position of the mercury column in the penetrometer stem.

APPENDIX G

APPARATUS AND TEST PROCEDURE FOR MEASUREMENT OF MECHANICAL PROPERTIES

Mechanical Properties From -200° to 800° F (144° to 700° K)

Apparatus and test procedure (Melpar).- In the determination of tensile and compressive strength properties of materials, Melpar utilizes a hydraulically powered universal testing machine with a capacity of 60,000 lbf (267 kN) and a screw-powered testing machine with a capacity of 10,000 lbf (45 kN).

The tensile specimen configuration is shown in figure G1. For compressive evaluations, a sample is 1 inch (2.54 cm) long with a cross section 1/2 by 1/2 inch (1.27 by 1.27 cm).

Either strain gages or extensometers are used to monitor strain. On the six ablation materials, foil strain gages with a 1/4-inch (0.63-cm) gage length were initially used to monitor strain for both tensile and compressive tests, but it was necessary to use extensometers at temperatures above 300° F (422° K) because melting of the samples caused erratic and spasmodic-strain readings which were obviously erroneous. In many cases it was not possible even to use extensometers because the molten condition of the sample surface caused deformation of the surface by the extensometer grips. In such cases, the strain was measured by monitoring the head movement of the machine, for compression tests. Strain gages were used up to 200° F (366° K) in compression tests and below room temperature for tensile tests. Extensometer measurements were made in tensile tests at and above room temperature.

Strain gages for measurements at low temperatures were cemented to the specimens. The bonding surface was roughened slightly, cleaned and degreased. The gage outline was then scribed lightly on the surface and adhesive accelerator was applied and allowed to dry completely. A small amount of adhesive was then applied to the specimen surface and the gage was pressed into place. In the case of the high-density phenolic-nylon samples, it was found that a 2 to 3 lb (9 to 13 N) clamping force applied through a layer of silicone rubber for approximately 60 seconds produced good bonds. A more porous surface such as that of the low-density phenolic-nylon did not form a bond as easily. Satisfactory results were obtained by bonding a thin teflon sheet to the material, and then bonding the gage to the teflon after its surface had been slightly roughened.

Tests at temperatures above ambient are made possible by use of suitable resistance heaters surrounding the specimens. Tests at cryogenic temperatures are made possible by liquid-nitrogen chambers in conjunction with resistance heaters. Tests at elevated temperatures were conducted after the specimen had been heated for 30 minutes. In some cases this time was not sufficient to assure a completely uniform temperature within the sample, but a longer heating period would have completely degraded the specimen.

APPENDIX G

Apparatus and test procedure (SRI).- At Southern Research Institute a universal testing machine with mechanical screw loading is the basic apparatus for the determination of tensile and compressive stress-strain properties. A load cell is used in measuring the applied load. The input voltage to the load cell is supplied by a constant-voltage dc power supply, and its output is read on an X-Y recorder. After the load-measurement system is installed in the apparatus, a final calibration of pen travel of the recorder is made by dead-weight loading. This procedure is repeated regularly throughout a testing program to maintain accurate calibration. A comparison of the recorded load with the visual dial gage of the testing machine during each test provides a further check on the calibration.

The configuration for the tensile specimen employed is shown in figure G2. The compression specimen is normally 1/2 by 1/2 by 1 in. (1.27 by 1.27 by 2.54 cm). The tensile specimens are loaded to fracture. Compressive specimens are usually loaded to 20 percent strain or fracture, whichever occurs first.

The basic features of the extensometers used to monitor axial strain are shown in figure G3. One extensometer is clipped on each side of the specimen. Insulators of steatite ceramic serve as rigid contact arms. While affording electrical and thermal insulation for the extensometer springs, the ceramic contact arms translate the elongation within the gage length into flexure of the springs. The strain gages are electrically connected into a bridge circuit. With two strain gages in tension and two in compression, all four gages in the circuit serve as both strain-measuring and as temperature-compensating devices. The output of the extensometer is proportional to the average strain along the two edges of the specimen. Calibration of the extensometers is made by using a micrometer accurate to 0.0001 inch (2.54 μm) and a shunt-resistor calibration circuit. The extensometer heads are actuated by the micrometer while the output signal is observed. The unit strain is then computed.

The basic features of the extensometers used to monitor lateral strains are shown in figure G4. Specimen motion due to strain is transmitted by pivoting heads, bearing directly on the specimen, to a differential transformer located at one end of the arms. To prevent false indications of small lateral motions of the specimen as strain, both the heads and arms are allowed to rotate. This arrangement assures flush contact of the heads with the specimen corners. A small spring located at the outer end of the extensometer provides sufficient force on the arms to follow the strain motion. A miniature vibrator is attached near the journal of the extensometer to eliminate static frictional forces within the journal. A sensitivity to a motion of 0.0001 inch (2.54 μm) is achieved. The output of the differential transformer is recorded on an oscillograph recorder. Calibration is performed by the same procedure as employed for the other extensometer.

In order to correlate the lateral-strain data recorded on the oscillograph recorder with the data obtained on the X-Y recorder, a timing device is incorporated to provide a signal to each recording instrument simultaneously.

For measurements above ambient temperature, specimens are heated radiantly by two high-intensity tungsten lamps. A rheostat is employed to regulate the

power to the lamps, and heating rates are controlled by programing the rheostat. Prior to obtaining the test data, several thermocouples were placed on the exterior faces and inside a spare sample and the lamps were positioned by trial and error to establish uniform heating for the samples. For both the low-density phenolic-nylon and the filled silicone resin, the temperature-rise rate to test temperature was about 100° F/min (0.926° K/s) at the specimen outside surface and 80° F/min (0.741° K/s) at the specimen center. These calibration tests also determined the time required at each temperature for the temperature to stabilize throughout the specimen.

Measurements at temperatures below ambient temperature are obtained by cooling the specimen with vapors from a liquid-nitrogen source. A cylindrical shield is placed around the specimen and the vapors are forced into the shield through a baffle arrangement. The circulation created provides uniform cooling.

APPENDIX G

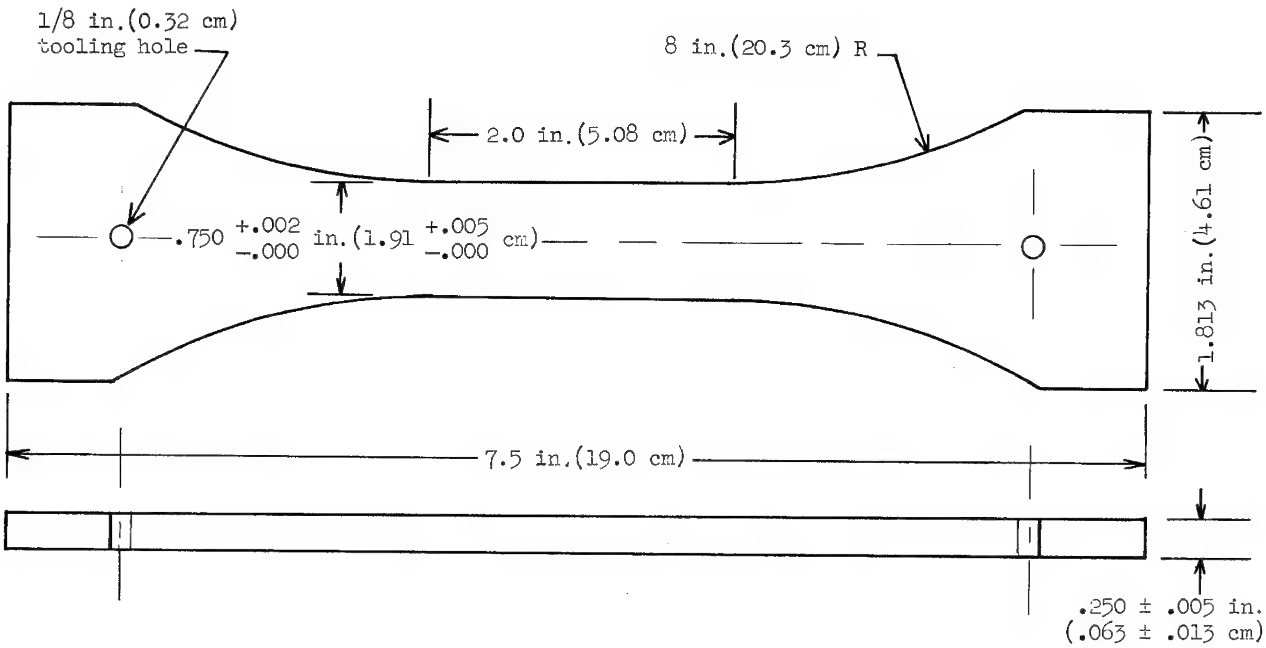


Figure G1.- Tensile specimen configuration for measurement of mechanical properties (Melpar).

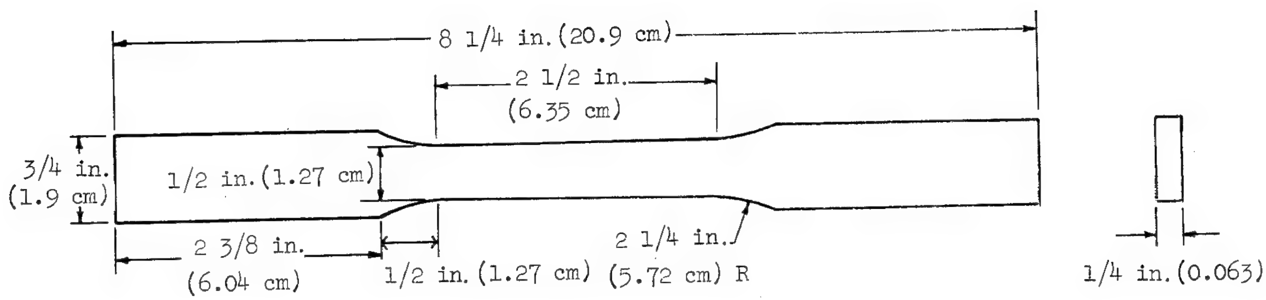


Figure G2.- Tensile specimen configuration for measurement of mechanical properties (SRI).

APPENDIX G

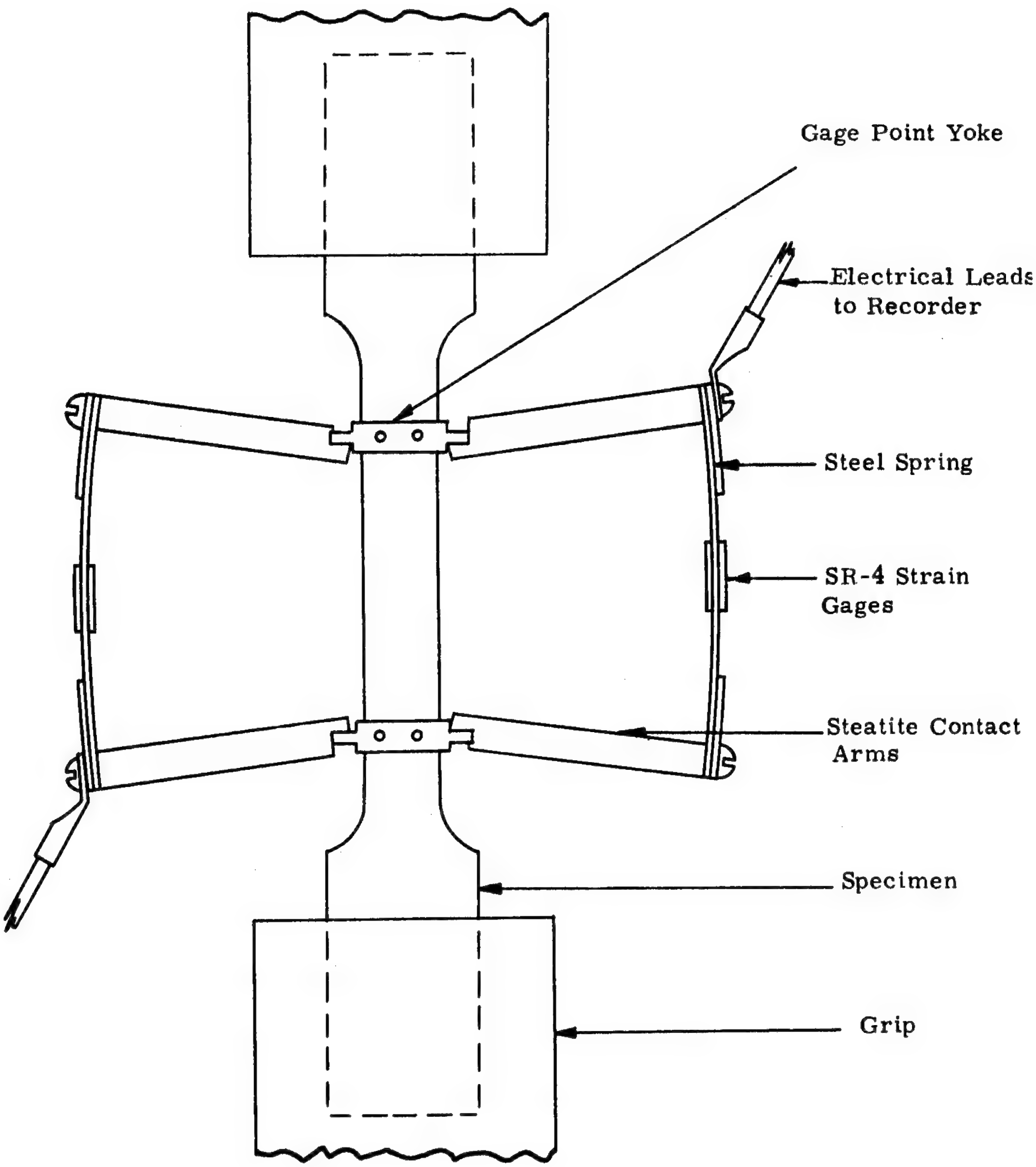


Figure G3.- Sketch of extensometer for measurement of axial strain (SRI).

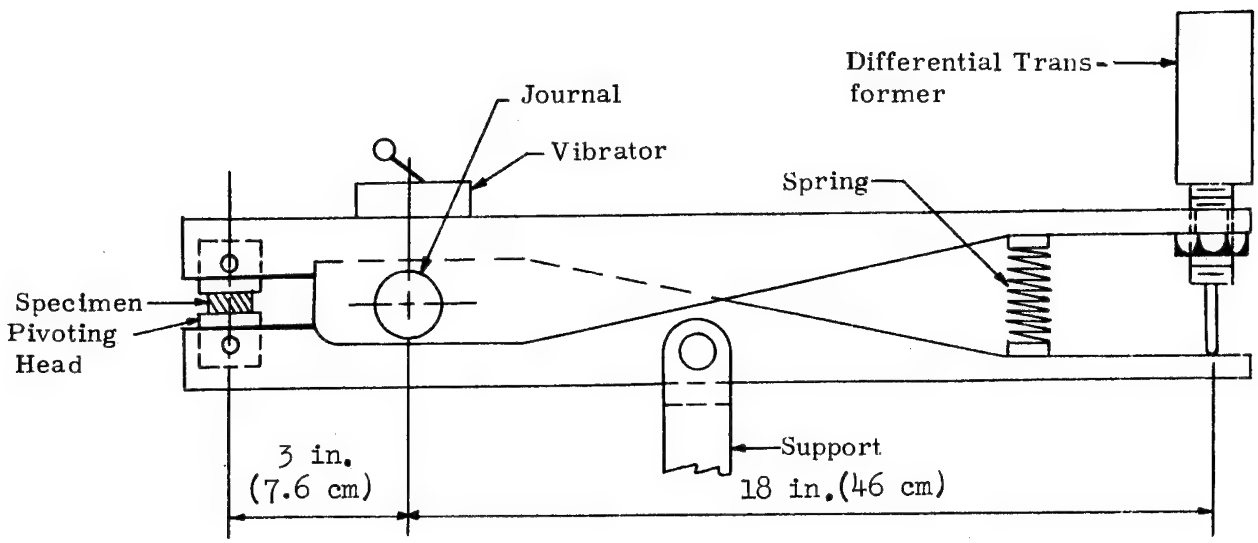


Figure G4.- Sketch of extensometer for measurement of lateral strain (SRI).

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LIST OF TABLES

TABLE 1.- ENTHALPY OF SIX CHARRING ABLATORS AND TWO CHARS

Ablation material	Temperature, °F	Temperature, °K	Enthalpy, Btu/lb	Enthalpy, MJ/kg	Weight loss, %
High-density phenolic-nylon (Melpar); reference temperature, 32° F (273° K)	[a]-191.2	149.0	-54.47	-0.1268	0
	-130.0	183.0	-43.96	-.1023	0
	-117.5	189.9	-42.01	-.0978	0
	-112.0	193.0	-39.76	-.0926	0
	-22.9	242.4	-16.54	-.0385	0
	-4.9	252.4	-11.36	-.0264	0
	32.0	272.9	0	0	0
	88.4	304.2	19.03	.0443	.4
	293.6	418.1	102.85	.2394	2.0
	295.4	419.1	101.23	.2357	2.0
	502.4	534.0	211.91	.4933	6.0
	509.0	537.6	214.00	.4982	6.1
	699.8	643.5	347.99	.8101	15.4
	752.0	672.5	386.41	.8996	20.9
Low-density phenolic-nylon (Melpar); reference temperature, 32° F (273° K)	[a]-184.0	153.0	-54.00	-.1257	0
	-156.1	168.5	-48.96	-.1140	0
	-131.8	182.0	-43.60	-.1015	0
	-73.0	214.6	-30.78	-.07153	0
	-13.0	247.9	-13.59	-.03158	0
	32.0	272.9	0	0	0
	75.8	297.2	14.45	.03358	.3
	76.1	297.4	14.69	.03413	.3
	212.0	372.8	65.74	.1530	1.2
	293.0	417.7	100.28	.2335	2.0
	299.0	421.1	103.73	.2415	2.1
	509.0	537.6	216.32	.5036	6.1
	689.0	637.5	338.56	.7882	14.7
	753.8	673.5	383.33	.8923	21.0
Low-density phenolic-nylon (SRI); reference temperature, 85° F (303° K)	[a]-320	78	-90.1	-.209	0
	-319	78	-99.1	-.230	0
	-280	100	-80.3	-.186	0
	-93.8	203.1	-46.5	-.108	0
	-93.8	203.1	-48.3	-.112	0
	-90.8	204.7	-45.7	-.106	0
	27.0	270.1	-21.1	-.0490	.2
	16.0	264.0	-19.1	-.0443	0
	95.5	308.1	6.7	.015	.2
	96.8	308.9	4.3	.0099	.1
	98.0	309.5	4.3	.0099	.1
	185.2	357.9	44.8	.104	1.1
	178.8	354.4	34.8	.0808	1.3
	273.0	406.6	74.2	.172	1.5
	322.2	434.0	87.8	.204	1.9
	300.3	421.8	90.0	.209	2.2
	428.3	492.8	154.4	.3588	4.4
	438.8	498.7	170.4	.3960	4.1
	519.0	543.2	203.7	.4733	5.2
	571.0	572.0	250.2	.5814	7.1
	619.2	598.8	258.2	.6000	26.0
	695.0	640.9	317.0	.7367	18.1
	727.0	658.6	317.2	.7371	38.0
	799.0	698.6	373.1	.8670	59.7

[a]Specimen 1.

TABLE 1.- ENTHALPY OF SIX CHARRING ABLATORS AND TWO CHARS - Continued

Ablation material	Temperature		Enthalpy		Weight loss, %
	°F	°K	Btu/lb	MJ/kg	
Filled silicone resin (Melpar); reference temperature, 32° F (273° K)	[a]-202.8	142.6	-77.76	-0.1810	0
	-202.0	143.0	-77.40	-.1802	0
	-195.1	146.9	-74.84	-.1742	0
	-78.7	211.5	-37.89	-.0882	0
	-13.0	247.9	-15.32	-.0357	0
	32.0	272.9	0	0	.2
	113.9	318.3	28.01	.0652	.5
	116.8	320.0	30.35	.0707	.5
	221.0	377.8	68.63	.1598	.8
	320.0	432.7	103.52	.2410	1.1
	513.4	540.1	185.65	.4322	2.0
	747.5	670.0	288.67	.6720	51.5
	753.8	673.5	290.84	.6771	52.5
Filled silicone resin (SRI); reference temperature, 85° F (303° K)	[a]-313	81	-101.9	-.237	0
	-305	86	-101.5	-.236	0
	-90	205	-62.3	-.145	0
	-86	207	-51.3	-.119	0
	0	255	-36.0	-.0837	0
	0	255	-34.9	-.0811	0
	144	355	19.4	.0451	0
	151	339	20.9	.0486	0
	184	357	29.0	.0674	0
	214	374	44.2	.103	.02
	243	390	56.8	.132	.17
	244	391	45.7	.106	0
	249	394	43.5	.101	.05
	304	424	77.0	.179	.70
	374	463	102.9	.239	.50
	383	468	105.1	.244	.60
	484	524	151.8	.353	1.70
	491	528	147.1	.342	1.60
	574	574	185.2	.430	3.00
	598	587	197.8	.460	3.10
	646	614	216.7	.504	9.30
	697	642	242.3	.563	33.00
	760	677	260.5	.605	31.00
Filled silicone resin in honeycomb (Melpar); reference temperature, 32° F (273° K)	[a]-202.0	143.0	-76.54	-.1782	0
	-132.7	181.5	-55.82	-.1299	0
	-35.5	235.4	-23.45	-.0546	0
	-34.6	235.9	-23.42	-.0545	0
	-13.9	247.4	-15.9	-.0370	0
	32	272.9	0	0	.2
	118.4	320.8	30.11	.0701	.4
	119.0	321.2	30.40	.0708	.4
	224.6	379.8	69.88	.1627	.9
	321.9	433.8	105.9	.2464	1.1
	322.4	434.1	105.9	.2465	1.1
	520.4	544.0	188.1	.4380	2.5
	752.0	672.5	290.0	.6750	52.4
	762.8	678.5	295.5	.6879	53.5

[a]Specimen 1.

TABLE 1.- ENTHALPY OF SIX CHARRING ABLATORS AND TWO CHARS - Concluded

Ablation material	Temperature, °F	Temperature, °K	Enthalpy, Btu/lb	Enthalpy, MJ/kg	Weight loss, %
Carbon-fiber-reinforced phenolic (Narmco 4028) (Melpar); reference temperature, 32° F (273° K)	[a]-220.6	132.7	-49.59	-0.1154	0
	-194.8	147.0	-46.13	-.1074	0
	-179.9	155.3	-43.97	-.1024	0
	-177.8	156.5	-43.15	-.1005	0
	-135.4	180.0	-36.90	-.0859	0
	-67.0	217.9	-24.17	-.0563	0
	17.5	264.8	-12.60	-.0293	0
	32.0	272.9	0	0	0
	76.2	297.4	12.28	.0286	0
	79.1	299.0	13.32	.0310	0
	136.8	331.1	29.05	.0676	0
	140.0	332.8	29.07	.0677	0
	324.5	435.2	88.43	.2059	.4
	521.6	544.6	163.46	.3805	1.8
	547.2	558.8	171.31	.3988	2.1
	752.0	672.5	252.02	.5867	6.6
	753.2	673.2	251.53	.5856	6.6
Low-density filled epoxy in honeycomb (Avcoat 5026-39-HC G) (Melpar); reference temperature, 32° F (273° K)	[a]-212.1	137.4	-56.63	-.1318	0
	-200.2	144.0	-54.14	-.1260	0
	-166.0	163.0	-48.78	-.1136	0
	-103.0	198.0	-36.59	-.0852	0
	-28.0	239.6	-18.18	-.0423	0
	-13.0	247.9	-14.76	-.0344	0
	32.0	272.9	0	0	.2
	78.8	298.9	15.68	.0365	.6
	79.0	299.0	15.77	.0367	.6
	302.0	422.7	95.74	.2229	4.1
	329.0	437.7	107.10	.2493	4.9
	502.0	533.7	176.78	.4115	11.2
	733.0	661.9	273.37	.6364	27.5
High-density phenolic-nylon char (SRI); reference temperature, 32° F (273° K)	[a]493	529	117.2	.2723	0
	1570	1127	355.4	.8259	.37
	1990	1360	654.1	1.520	.37
	2550	1671	1190.7	2.7672	1.12
	3005	1923	1272.5	2.9573	.76
	3040	1943	1344.8	3.1253	2.67
	3500	2198	1549.8	3.6017	1.18
	4490	2747	2158.6	5.0166	-1.61
	5010	3036	2759.4	6.4128	3.95
	4040	2498	2087.3	4.8509	.79
	[b]1030	827	188.1	.4371	1.03
	1595	1141	388.6	.9031	.35
	2050	1393	869.0	2.019	.35
	3545	2223	1638.4	3.8076	1.06
	4025	2489	1905.1	4.4275	.36
	4490	2747	2583.4	6.0038	.36
	5045	3055	3105.9	7.2181	1.43
	[c]2040	1388	740.2	1.720	1.00
	3170	2015	1570.7	3.6503	5.07
	[d]5055	3061	2556.1	5.9404	3.34
Low-density phenolic-nylon char (SRI); reference temperature, 32° F (273° K)	[a]1043	834	225.6	.5243	14.1
	2525	1657	994.6	2.311	3.1
	3075	1962	1300.2	3.0217	4.5
	3600	2253	1581.4	3.6752	.4
	4020	2486	1518.6	3.5292	5.9
	4505	2756	2004.7	4.6589	.4
	4545	2778	1881.0	4.3714	1.9
	5045	3055	2477.5	5.7577	2.6
	[b]985	802	190.2	.4420	3.6
	1495	1085	481.5	1.119	2.8
	1985	1357	562.7	1.308	4.8
	2525	1657	1153.4	2.6805	3.6
	3050	1948	1278.0	2.7901	1.6
	3550	2226	1600.2	3.7189	5.6
	4025	2489	1746.4	4.0586	-.4
	4505	2756	1966.2	4.5694	1.9
	5025	3044	2326.2	5.4061	10.1

[a]Specimen 1.
[b]Specimen 2.
[c]Specimen 3.
[d]Specimen 4.

TABLE 2.- SPECIFIC HEAT OF SIX CHARRING ABLATORS AND TWO CHARS

Ablation material	Temperature		Specific heat	
	°F	°K	Btu/lb-°F	kJ/kg-°K
High-density and low-density phenolic-nylon (Melpar)	-200	144	0.165	0.690
	-150	172	.200	.837
	-100	200	.235	.983
	-50	228	.267	1.12
	0	255	.300	1.25
	50	283	.331	1.38
	100	311	.361	1.51
	150	339	.393	1.64
	200	366	.423	1.77
	250	394	.453	1.89
	300	422	.484	2.02
	350	450	.513	2.15
	400	477	.542	2.27
	450	505	.571	2.39
	500	533	.599	2.51
	550	561	.628	2.63
	600	588	.659	2.76
	650	616	.684	2.86
	700	644	.711	2.97
	750	671	.740	3.10
Filled silicone resin and filled silicone resin in honeycomb (Melpar)	-200	144	.284	1.19
	-150	172	.301	1.26
	-100	200	.316	1.32
	-50	228	.330	1.38
	0	255	.340	1.42
	50	283	.354	1.48
	100	311	.365	1.53
	150	339	.372	1.56
	200	366	.382	1.60
	250	394	.390	1.63
	300	422	.396	1.66
	350	450	.404	1.69
	400	477	.410	1.72
	450	505	.415	1.74
	500	533	.419	1.75
	550	561	.423	1.77
	600	588	.427	1.79
	650	616	.430	1.80
	700	644	.433	1.81
	750	671	.435	1.82
Carbon-fiber-reinforced phenolic (Narmco 4028) (Melpar)	-200	144	.126	.527
	-150	172	.164	.686
	-100	200	.192	.803
	-50	228	.221	.924
	0	255	.245	1.02
	50	283	.267	1.12
	100	311	.287	1.20
	150	339	.304	1.27
	200	366	.320	1.34
	250	394	.334	1.40
	300	422	.346	1.45
	350	450	.358	1.50
	400	477	.367	1.54
	450	505	.375	1.57
	500	533	.384	1.61
	550	561	.390	1.63
	600	588	.395	1.65
	650	616	.400	1.67
	700	644	.405	1.69
	750	671	.408	1.71
Low-density filled epoxy in honeycomb (Avcoat 5026-39-HC G) (Melpar)	-200	144	0.145	0.606
	-150	172	.189	.791
	-100	200	.224	.937
	-50	228	.256	1.07
	0	255	.284	1.19
	50	283	.307	1.28
	100	311	.329	1.38
	150	339	.347	1.45
	200	366	.364	1.52
	250	394	.376	1.57
	300	422	.397	1.66
	350	450	.399	1.67
	400	477	.406	1.70
	450	505	.413	1.73
	500	533	.418	1.75
	550	561	.420	1.76
	600	588	.424	1.77
	650	616	.424	1.77
	700	644	.425	1.78
	750	671	.425	1.78
High-density phenolic-nylon char (SRI)	500	532	.22	.92
	1000	810	.35	1.5
	1500	1088	.50	2.1
	2000	1365	.63	2.6
	2500	1643	.67	2.8
	3000	1920	.67	2.8
	3500	2198	.67	2.8
	4000	2475	.67	2.8
	4500	2753	.67	2.8
	5000	3030	.67	2.8
Low-density phenolic-nylon char (SRI)	1000	810	.39	1.6
	2000	1365	.52	2.2
	3000	1920	.52	2.2
	4000	2475	.52	2.2
	5000	3030	.52	2.2

TABLE 3.- THERMAL CONDUCTIVITY OF SIX CHARRING ABLATORS

AND TWO CHARS

Ablation material	Mean temperature		Thermal conductivity		Average ΔT	
	°F	°K	Btu/ft-hr-°F	W/m-°K	°F	°K
High-density phenolic-nylon (Melpar)	[a]-184	153	0.147	0.255	------	-----
	-123	187	.166	.287	------	-----
	81	300	.201	.348	------	-----
	140	333	.200	.346	------	-----
	270	405	.205	.355	------	-----
	275	408	.204	.353	------	-----
	276	408	.207	.358	------	-----
	[b]381	467	.207	.358	------	-----
	[c]424	490	.206	.357	------	-----
	[d]-195	147	.141	.244	------	-----
	-95	202	.169	.292	------	-----
	-20	244	.186	.322	------	-----
	74	296	.192	.332	------	-----
	199	366	.195	.337	------	-----
	310	427	.195	.337	------	-----
	334	440	.196	.339	------	-----
	[e]390	472	.187	.324	------	-----
	[f]500	533	.085	.147	------	-----
Low-density phenolic-nylon (Melpar)	[a]-269	106	.0359	.0621	------	-----
	-161	166	.0549	.0950	------	-----
	-90	205	.0614	.106	------	-----
	88	304	.0745	.129	------	-----
	334	440	.0761	.132	------	-----
	[b]403	479	.0751	.130	------	-----
	[c]415	485	.0733	.127	------	-----
	[d]-213	137	.0472	.0817	------	-----
	-112	193	.0581	.101	------	-----
	-105	197	.0606	.105	------	-----
	174	353	.0748	.129	------	-----
	217	375	.0760	.132	------	-----
	311	428	.0735	.127	------	-----
	[e]480	521	.0694	.120	------	-----
	[f]194	363	.0721	.125	------	-----
	306	425	.0714	.124	------	-----
	356	453	.0689	.119	------	-----

[a]Specimen 1.
[b]Specimen 2.
[c]Specimen 3.
[d]Specimen 4.
[e]Specimen 5.
[f]Specimen 6.

TABLE 3.- THERMAL CONDUCTIVITY OF SIX CHARRING ABLATORS

AND TWO CHARS - Continued

Ablation material	Mean temperature		Thermal conductivity		Average ΔT	
	°F	°K	Btu/ft-hr-°F	W/m-°K	°F	°K
Low-density phenolic-nylon (SRI)	[a]-23.8	241.9	0.058	0.101	45.8	25.4
	98.5	309.8	.065	.113	191.3	106.2
	130.7	327.6	.054	.094	62.2	34.5
	139.1	332.3	.057	.099	60.5	33.6
	234.1	385.1	.048	.083	145.5	80.8
	331.3	439.0	.051	.088	231.7	128.6
	349.6	449.2	.053	.092	234.6	130.2
	457.9	509.3	.062	.108	331.4	183.9
	552.0	561.5	.060	.104	299.3	166.1
	762.0	678.0	.052	.090	255.4	141.7
	[b]-34.6	235.9	.062	.108	34.6	19.2
	71.7	294.9	.050	.087	142.3	79.0
	188.1	359.5	.063	.109	134.1	74.4
	322.4	434.1	.054	.094	187.0	103.8
	433.1	495.5	.058	.101	251.5	139.6
	550.0	560.4	.062	.108	338.2	187.7
	695.1	640.9	.060	.104	376.5	209.0
	922.8	767.3	.070	.121	207.4	115.1
	[c]-37.1	234.5	.063	.109	33.6	18.6
	86.8	303.3	.051	.088	137.9	76.5
	186.4	358.6	.051	.088	112.8	62.6
	251.2	394.5	.050	.087	114.8	63.7
	367.6	459.2	.050	.087	174.2	96.7
	673.6	629.0	.062	.108	230.3	127.8
	863.9	734.6	.065	.113	270.8	115.3
	[d]-108	195	.068	.118	203	113
	-118	190	.065	.113	200	111
	-210	139	.060	.104	110	61
	-267	107	.057	.099	52.8	29.3
	[e]-48.6	228.2	.073	.127	272	151.0
	-65.6	218.7	.073	.127	251	139.3
	-159.3	166.7	.058	.101	157	87
	[f]144	335.2	.048	.083	52.0	29

[a]Specimen 1.
[b]Specimen 2.
[c]Specimen 3.
[d]Specimen 4.
[e]Specimen 5.
[f]Specimen 6.

TABLE 3.- THERMAL CONDUCTIVITY OF SIX CHARRING ABLATORS

AND TWO CHARS - Continued

Ablation material	Mean temperature		Thermal conductivity		Average ΔT	
	°F	°K	Btu/ft-hr-°F	W/m-°K	°F	°K
Filled silicone resin (Melpar)	[a]-197	146	0.0500	0.0865	------	-----
	-152	171	.0542	.0938	------	-----
	351	450	.0734	.127	------	-----
	[b]446	503	.0774	.134	------	-----
	[c]693	640	.0631	.109	------	-----
	[d]-199	145	.0518	.0896	------	-----
	-125	186	.0590	.102	------	-----
	109	316	.0741	.128	------	-----
	305	424	.0777	.134	------	-----
	[e]661	622	.0548	.0948	------	-----
	[f]86	303	.0642	.111	------	-----
	115	319	.0630	.109	------	-----
	259	399	.0641	.111	------	-----
	448	504	.0641	.111	------	-----
	[g]669	626	.0558	.0965	------	-----
	[h]683	634	.0561	.0971	------	-----
Filled silicone resin (SRI)	[a]172	351	.053	.092	81	45
	221	378	.050	.087	183	102
	236	386	.055	.095	125	69
	346	447	.062	.108	195	108
	433	496	.067	.116	149	83
	605	591	.048	.083	247	137
	728	660	.057	.099	284	158
	[b]-48	229	.066	.114	33	18
	43	279	.058	.101	130	72
	98	310	.057	.099	94	52
	130	327	.058	.101	81	45
	179	355	.060	.104	113	63
	405	480	.069	.120	171	95
	510	539	.060	.104	224	124
	614	596	.057	.099	287	159
	728	660	.058	.101	326	181
	[c]313	429	.065	.113	177	98
	[d]-82	210	.068	.118	251	139
	-164	164	.056	.097	163	90
	[e]-31	238	.066	.114	125	69
	-255	114	.042	.073	76	42

[a]Specimen 1.
[b]Specimen 2.
[c]Specimen 3.
[d]Specimen 4.
[e]Specimen 5.
[f]Specimen 6.
[g]Specimen 7.
[h]Specimen 8.

TABLE 3.- THERMAL CONDUCTIVITY OF SIX CHARRING ABLATORS

AND TWO CHARS - Continued

Ablation material	Mean temperature		Thermal conductivity		Average ΔT	
	°F	°K	Btu/ft-hr-°F	W/m-°K	°F	°K
Filled silicone resin in honeycomb; direction A (Melpar)	[a]-177	157	0.0450	0.0778	------	-----
	-121	188	.0506	.0875	------	-----
	-15	247	.0605	.105	------	-----
	61	289	.0614	.106	------	-----
	165	347	.0641	.111	------	-----
	282	412	.0617	.107	------	-----
	396	475	.0648	.112	------	-----
	[b]536	553	.0622	.108	------	-----
	[c]646	614	.0566	.0979	------	-----
	[d]-159	167	.0460	.0796	------	-----
	-40	233	.0590	.102	------	-----
	97	309	.0619	.107	------	-----
	176	353	.0622	.108	------	-----
	306	425	.0639	.111	------	-----
	[e]417	487	.0644	.111	------	-----
	[f]559	565	.0602	.104	------	-----
	[g]669	626	.0627	.109	------	-----
Filled silicone resin in honeycomb; direction B (Melpar)	[a]-173	159	.0484	.0837	------	-----
	-83	209	.0588	.102	------	-----
	9	260	.0639	.111	------	-----
	165	347	.0689	.119	------	-----
	358	454	.0692	.120	------	-----
	[b]523	545	.0673	.116	------	-----
	[c]655	619	.0573	.0991	------	-----
	[d]-152	171	.0508	.0879	------	-----
	-108	195	.0566	.0979	------	-----
	43	279	.0658	.114	------	-----
	176	353	.0677	.117	------	-----
	291	417	.0651	.113	------	-----
	385	469	.0665	.115	------	-----
	[e]581	578	.0653	.113	------	-----
	[f]682	634	.0561	.097	------	-----

[a]Specimen 1.
[b]Specimen 2.
[c]Specimen 3.
[d]Specimen 4.
[e]Specimen 5.
[f]Specimen 6.
[g]Specimen 7.

TABLE 3.- THERMAL CONDUCTIVITY OF SIX CHARRING ABLATORS

AND TWO CHARS - Continued

Ablation material	Mean temperature		Thermal conductivity		Average ΔT	
	°F	°K	Btu/ft-hr-°F	W/m-°K	°F	°K
Filled silicone resin in honeycomb; direction C (Melpar)	[a]-188	151	0.0538	0.0931	------	-----
	-117	190	.0628	.109	------	-----
	43	279	.0720	.125	------	-----
	329	438	.0716	.124	------	-----
	352	450	.0730	.126	------	-----
	[b]-166	163	.0544	.0931	------	-----
	-97	201	.0617	.109	------	-----
	-81	210	.0673	.125	------	-----
	18	265	.0687	.124	------	-----
	172	351	.0750	.126	------	-----
	183	357	.0714	.0941	------	-----
	329	438	.0714	.107		
	[c]484	524	.0704	.116	------	-----
	[d]559	565	.0702	.119	------	-----
	[e]587	581	.0692	.130	------	-----
	[f]651	616	.0629	.123	------	-----
	692	639	.0629	.123	------	-----
Carbon-fiber-reinforced phenolic (Narmco 4028) (Melpar)	[a]-195	147	.121	.209	------	-----
	-111	194	.163	.282	------	-----
	12	262	.212	.367		
	129	327	.255	.441	------	-----
	[b]-188	151	.129	.223	------	-----
	-91	205	.165	.286	------	-----
	-6	252	.186	.322	------	-----
	172	351	.264	.458	------	-----
	[c]300	422	.309	.534	------	-----
	[d]341	444	.324	.561	------	-----
	[e]475	519	.353	.611	------	-----
	[f]556	564	.348	.602	------	-----
	[g]628	604	.321	.555	------	-----
	[h]680	633	.343	.593	------	-----
	[i]716	653	.344	.595	------	-----
	[j]755	674	.336	.581	------	-----
	[k]752	672	.332	.574	------	-----

[a]Specimen 1.
[b]Specimen 2.
[c]Specimen 3.
[d]Specimen 4.
[e]Specimen 5.
[f]Specimen 6.
[g]Specimen 7.
[h]Specimen 8.
[i]Specimen 9.
[j]Specimen 10.
[k]Specimen 11.

TABLE 3.- THERMAL CONDUCTIVITY OF SIX CHARRING ABLATORS AND TWO CHARS - Continued

Ablation material	Mean temperature		Thermal conductivity		Average ΔT	
	°F	°K	Btu/ft-hr-°F	W/m-°K	°F	°K
Low-density filled epoxy in honeycomb; (Avcoat 5026-39-HC G) direction C (Melpar)	[a]-182	154	0.0290	0.0502	------	-----
	-92	204	.0382	.0661	------	-----
	140	333	.0469	.0811	------	-----
	[b]-194	147	.0312	.0540	------	-----
	-94	203	.0346	.0599	------	-----
	-57	223	.0365	.0631	------	-----
	-144	335	.0469	.0811	------	-----
	[c]268	404	.0506	.0875	------	-----
	[d]275	408	.0532	.0920	------	-----
	[e]491	528	.0631	.109	------	-----
	[f]513	540	.0605	.105	------	-----
	[g]610	594	.0615	.106	------	-----
	[h]675	630	.0573	.0991	------	-----
	[i]784	690	.0513	.0887	------	-----
	[j]790	694	.0472	.0817	------	-----

[a]Specimen 1.
[b]Specimen 2.
[c]Specimen 3.
[d]Specimen 4.
[e]Specimen 5.
[f]Specimen 6.
[g]Specimen 7.
[h]Specimen 8.
[i]Specimen 9.
[j]Specimen 10.

TABLE 3.- THERMAL CONDUCTIVITY OF SIX CHARRING ABLATORS

AND TWO CHARS - Continued

Ablation material	Mean temperature		Thermal conductivity		Average ΔT	
	°F	°K	Btu/ft-hr-°F	W/m-°K	°F	°K
High-density phenolic-nylon char (SRI)	[a]867	736	0.336	0.580	530	294
	870	738	.346	.598	528	293
	875	741	.351	.606	529	294
	1230	938	.521	.901	513	285
	1234	940	.533	.922	512	284
	1236	941	.561	.971	511	284
	1239	943	.566	.978	511	284
	1604	1146	.665	1.15	553	307
	1608	1148	.700	1.21	559	310
	1608	1148	.695	1.20	559	310
	2147	1447	.747	1.29	630	350
	2154	1451	.780	1.35	628	349
	2156	1452	.795	1.37	628	349
	2158	1453	.786	1.36	624	346
	2570	1682	.991	1.71	608	337
	2573	1683	1.02	1.77	604	335
	2577	1686	1.07	1.84	600	333
	2580	1687	1.06	1.83	596	331
	2995	1918	1.42	2.45	495	275
	3000	1920	1.42	2.45	500	278
	3010	1926	1.49	2.58	490	272
	3000	1920	1.47	2.55	500	278
	3720	2320	1.32	2.29	770	427
	3770	2348	1.42	2.45	750	416
	3910	2425	1.69	2.93	610	339
	3910	2425	1.73	3.00	610	339
	3930	2436	1.81	3.13	590	327
	[b]730	660	.607	1.05	229.5	127.4
	733	662	.593	1.03	229.7	127.5
	734	663	.580	1.00	230.1	127.7
	1132	884	.691	1.20	311	173
	1137	886	.676	1.17	316	175
	1140	888	.703	1.22	313	174
	1695	1196	.766	1.33	423	235
	1699	1198	.755	1.31	424	235
	1701	1199	.810	1.40	423	235
	1705	1202	.747	1.29	423	235
	2250	1504	.841	1.46	610	339
	2250	1504	.866	1.50	600	333
	2725	1768	.850	1.47	800	444
	2730	1770	.925	1.60	730	405
	3590	2248	1.37	2.38	660	366
	3610	2259	1.45	2.51	640	355
	4130	2547	1.84	3.18	600	333
	4110	2536	1.82	3.16	620	344
	4040	2498	1.89	3.27	580	322
	4620	2819	2.47	4.27	580	322
	4600	2808	2.47	4.27	580	322
	4610	2814	2.38	4.12	580	322
	[c]1913	1317	.676	1.17	462	256
	1914	1318	.642	1.11	476	264
	2320	1543	.791	1.37	480	266
	2318	1542	.767	1.33	492	273
	2334	1551	.751	1.30	506	281

[a]Specimen 1.
[b]Specimen 2.
[c]Specimen 3.

TABLE 3.- THERMAL CONDUCTIVITY OF SIX CHARRING ABLATORS

AND TWO CHARS - Concluded

Ablation material	Mean temperature		Thermal conductivity		Average ΔT	
	°F	°K	Btu/ft-hr-°F	W/m-°K	°F	°K
Low-density phenolic-nylon char (SRI)	[a]797	698	0.58	1.0	370	205
	797	698	.62	1.1	372	206
	796	697	.57	.99	372	206
	797	698	.58	1.00	375	208
	1345	993	.942	1.63	472	262
	1347	1003	.883	1.53	480	266
	1347	1003	.82	1.4	483	268
	1347	1003	.81	1.4	485	269
	1963	1345	1.12	1.93	578	321
	1966	1346	1.07	1.85	583	324
	1969	1348	1.07	1.85	585	325
	2610	1704	1.37	2.37	905	502
	2630	1715	1.41	2.44	905	502
	3140	1998	1.47	2.54	1060	588
	3140	1998	1.49	2.58	1060	588
	3140	1998	1.52	2.63	1060	588
	3650	2026	1.62	2.80	1170	649
	3670	2292	1.71	2.96	1170	649
	3670	2292	1.72	2.98	1170	649
	4300	2642	2.39	4.13	950	527
	4300	2642	2.40	4.15	950	527
	4360	2685	2.41	4.17	950	527
	[b]1174	907	.73	1.26	606	336
	1176	908	.71	1.23	606	336
	1179	910	.72	1.25	610	339
	1180	910	.70	1.21	610	339
	1473	1073	.858	1.48	667	370
	1473	1073	.867	1.50	669	371
	1473	1073	.858	1.48	669	371
	2270	1515	1.04	1.80	1057	587
	2270	1515	1.11	1.92	1057	587
	2270	1515	1.12	1.94	1057	587
	2870	1848	1.35	2.34	786	436
	2870	1848	1.36	2.35	786	436
	2870	1848	1.33	2.30	786	436
	3710	2314	2.55	4.41	553	307
	3710	2314	2.55	4.41	553	307
	3710	2314	2.63	4.55	553	307
	4335	2661	2.37	4.10	850	472
	4335	2661	2.39	4.13	850	472
	4335	2661	2.41	4.17	850	472

[a]Specimen 1.
[b]Specimen 2.

TABLE 4.- THERMAL EXPANSION OF SIX CHARRING ABLATORS

Ablation material	Temperature, °F	Temperature, °K	Expansion, mils/in. (mm/m)
High-density phenolic-nylon (Melpar)	[a]-200	144	-7.15
	-148	173	-6.21
	-100	200	-5.10
	-58	223	-4.12
	0	255	-2.65
	32	273	-1.75
	80	300	.00
	104	313	1.00
	212	373	7.39
	284	413	12.23
	320	433	14.55
	356	453	17.19
	374	463	18.00
	[b]-202	143	-7.07
	-148	173	-5.98
	-92	204	-4.76
	-49	228	-3.70
	0	255	-2.45
	32	273	-1.55
	75	297	.00
	104	313	1.00
	140	333	2.40
	212	373	6.91
	248	393	8.88
	[c]320	433	13.79
	[d]392	473	19.00
Low-density phenolic-nylon (Melpar)	[a]-204	142	-6.18
	-148	173	-5.27
	-103	198	-4.39
	-60	222	-3.52
	-26	241	-2.79
	-8	251	-2.37
	32	273	-1.33
	79	299	.00
	104	313	.70
	212	373	4.05
	284	413	6.31
	320	433	7.20
	[b]387	470	7.92
	[c]-193	148	-5.87
	-148	173	-5.08
	-103	198	-4.20
	-58	223	-3.28
	-8	251	-2.16
	63	290	-.40
	78	299	.00
	90	305	.55
	125	325	1.76
	144	335	1.80
	164	346	2.38
	197	365	4.00
	289	416	6.78
	[d]337	442	7.33
	[e]390	472	7.55

[a]Specimen 1.
[b]Specimen 2.
[c]Specimen 3.
[d]Specimen 4.
[e]Specimen 5.

TABLE 4.- THERMAL EXPANSION OF SIX CHARRING ABLATORS - Continued

Ablation material	Temperature		Expansion
	°F	°K	mils/in. (mm/m)
Low-density phenolic-nylon (SRI)	[a]79.7	299.4	0
	35.4	274.8	-1.00
	-105	197	-4.20
	-320	78	-7.80
	-271	105	-7.00
	-187	152	-5.70
	-121	188	-4.70
	-73	215	-3.60
	52	284	-.90
	79.7	299.4	-.07
	156	342	2.77
	242	390	5.73
	374	463	5.00
	445	502	4.30
	553	562	1.93
	650	616	-2.80
	719	654	-88.30
	622	601	-95.00
	445	502	-89.50
	369	460	-89.10
	[b]79.7	299.4	0
	15.0	263.5	1.93
	-103	198	-4.40
	-318	79	-8.20
	-178	157	-5.63
	-66.8	218.1	-3.33
	40.1	277.4	-.93
	80.3	299.7	0
	173	351	4.30
	265	402	7.03
	348	448	4.63
	465	513	5.30
	570	572	3.07
	675	630	-8.83
	783	690	-45.40
	634	607	-46.10
	579	577	-50.30
	529	549	-50.50
	459	510	-50.60
	383	468	-51.10
	79.7	299.4	-51.10
	[c]79.7	299.4	0
	33.1	273.5	-1.27
	-99	200	-4.30
	-318	79	-8.07
	-227	129	-6.83
	-187	152	-6.00
	-144	175	-5.30
	-22.7	242.5	-2.73
	61.5	289.3	-.67
	78.0	298.4	-.07
	74.3	296.4	0
	107	314.7	.93
Low-density phenolic-nylon (SRI) (continued)	150	339	2.40
	201	367	4.57
	161	345	2.50
	112	317	.83
	74.3	296.4	-.07
	79.7	299.4	0
	152	340	2.03
	166	347	2.53
	253	396	4.90
	264	402	4.92
	275	408	4.91
	303	423	4.91
	316	431	5.20
	335	441	5.70
	349	449	6.03
	379	466	6.63
	406	481	6.80
	432	495	6.80
	475	519	6.73
	516	542	6.20
	548	559	6.67
	607	592	4.00
	634	607	1.73
	651	617	.70
	665	624	-.47
	614	596	-4.00
	526	547	-6.13
	494	529	-6.90
	76.6	297.6	-17.23
	[d]79.7	299.4	0
	104	313	.70
	133	329	1.77
	169	349	2.10
	198	365	2.30
	238	387	3.07
	270	405	3.33
	304	424	3.60
	343	446	3.57
	376	464	3.83
	413	485	4.03
	481	522	4.00
	406	481	3.33
	546	558	2.23
	582	578	.20
	655	619	-1.97
	681	633	-3.47
	709	649	-7.00
	741	667	-38.70
	769	682	-66.67
	643	612	-76.50
	548	559	-79.20
	79.7	299.4	-91.26

[a]Specimen 1.
[b]Specimen 2.
[c]Specimen 3.
[d]Specimen 4.

TABLE 4.- THERMAL EXPANSION OF SIX CHARRING ABLATORS - Continued

Ablation material	Temperature, °F	Temperature, °K	Expansion, mils/in. (mm/m)
Filled silicone resin (Melpar)	[a]-222	132	-20.58
	-155	169	-16.57
	-110	194	-13.40
	-40	233	-8.30
	32	273	-3.50
	133	329	3.56
	154	341	4.99
	251	395	10.59
	324	435	14.89
	387	470	18.10
	[b]-180	155	-18.00
	-150	172	-15.90
	-125	186	-14.20
	-110	194	-13.15
	-50	228	-8.80
	32	273	-3.10
	77	298	.00
	135	330	3.35
	146	336	4.30
	148	337	4.81
	258	398	10.70
	335	441	15.00
	405	480	18.18
Filled silicone resin (SRI)	[a]80	300	0
	32	273	-2.73
	-59	222	-8.45
	-100	200	-11.20
	-320	77	-17.90
	-221	132	-15.30
	-54	225	-9.61
	-18	245	-6.65
	74	296	-.23
	100	311	1.20
	151	339	4.86
	203	368	8.65
	252	395	12.00
	301	422	15.60
	360	455	19.50
	397	476	22.75
	455	508	26.40
	499	532	28.10
	534	552	27.90
	599	588	27.90
	642	612	13.30
	[b]79	299	0
	32	273	-3.00
	-102	198	-13.60
	-318	79	-23.60
	-229	158	-21.90
	-38	234	-9.90
	76	297	-.90
	109	316	-1.78
	128	326	3.15
	156	342	5.15
	180	355	6.90
	217	376	9.40
	263	401	12.80
	287	415	14.50
	324	435	17.00
	360	455	20.00
	396	475	30.90
	432	495	29.60
	469	516	31.30
	506	536	33.50
	544	557	37.20
	584	580	40.30
	615	597	36.10
	655	619	1.35
	651	616	-75.00
	628	604	-97.10
	[c]79	299	0
	36	275	-2.33
	-103	198	-12.52
	-320	77	-23.21
	-253	115	-20.81
	-166	163	-18.32
	-85	201	-16.65
	33	274	-3.76
	79	299	-.57
Filled silicone resin in honeycomb; direction A (Melpar)	[a]-200	144	-16.71
	-180	155	-15.48
	-119	189	-11.61
	-112	193	-10.92
	-50	228	-7.65
	32	273	-2.70
	80	300	.00
	162	345	4.59
	221	378	7.85
	239	388	8.61
	378	465	15.10
	[b]435	497	17.06
	[c]-195	147	-16.20
	-125	186	-11.59
	-112	193	-11.39
	-46	230	-6.80
	0	255	-4.69
	32	273	-2.62
	78	299	.00
	163	346	4.30
	173	351	5.00
	204	369	6.80
	342	445	13.98
	[d]395	475	15.70
	[e]405	480	15.80
Filled silicone resin in honeycomb; direction B (Melpar)	[a]-200	144	-21.91
	-180	155	-20.06
	-119	189	-14.94
	0	255	-6.10
	32	273	-3.60
	81	300	.00
	151	339	5.11
	214	374	9.57
	253	396	12.33
	342	445	18.62
	[b]414	485	21.00
	[c]-179	156	-20.40
	-119	189	-15.40
	-110	194	-15.40
	-50	228	-9.41
	12	262	-4.85
	79	299	.00
	147	337	4.50
	159	344	5.60
	163	346	6.00
	164	346	5.95
	220	377	10.60
	245	391	12.59
	252	395	13.09
	[d]387	470	20.50
	[e]389	471	20.80
	[f]409	482	21.30
Filled silicone resin in honeycomb; direction C (Melpar)	[a]-200	144	-7.87
	-148	173	-5.82
	-109	195	-4.49
	0	255	-1.75
	32	273	-1.04
	80	300	.00
	144	335	1.35
	149	338	1.42
	162	345	1.60
	252	395	3.12
	[b]381	467	4.75
	392	473	4.93
	397	476	4.96
	[c]-194	148	-7.25
	-180	155	-6.63
	-169	162	-6.50
	-148	173	-5.48
	-109	195	-4.43
	-40	233	-2.61
	32	273	-1.10
	78	299	.00
	144	335	1.28
	156	342	1.63
	248	393	3.69
	354	452	5.54
	369	460	5.92
	392	473	5.93
	[d]342	445	6.99
	381	467	7.45
	396	475	7.65
	405	480	7.71

[a]Specimen 1.
[b]Specimen 2.
[c]Specimen 3.
[d]Specimen 4.
[e]Specimen 5.
[f]Specimen 6.

TABLE 4.- THERMAL EXPANSION OF SIX CHARRING ABLATORS - Concluded

Ablation material	Temperature		Expansion
	°F	°K	mils/in. (mm/m)
Carbon-fiber-reinforced phenolic (Narmco 4028) (Melpar)	[a]-143	176	-1.98
	-138	179	-1.93
	-86	208	-1.45
	-20	244	-.95
	5	258	-.67
	55	286	-.16
	75	297	.00
	226	381	1.78
	330	438	3.20
	[b]-225	130	-2.57
	-143	176	-1.92
	-99	200	-1.65
	-40	233	-1.15
	-8	251	-.80
	24	269	-.45
	75	297	.00
	95	308	.19
	299	421	2.19
	363	457	3.52
	[c]412	484	3.72
	[d]437	498	6.34
	[e]479	521	12.90
	[f]509	538	12.20
	[g]517	542	18.70
	[h]517	542	19.40
	[i]539	554	19.40
	[j]588	582	23.30
	[k]618	598	24.40
	[l]648	615	25.80
	[m]750	672	26.30
Filled epoxy in honeycomb (Avcoat 5026-39-HC G); direction A (Melpar)	[a]-195	147	-4.78
	-100	200	-3.47
	7	259	-1.60
	75	297	.00
	94	307	.26
	137	331	1.22
	[b]-177	157	-4.55
	-100	200	-3.55
	13	263	-1.56
	75	297	.00
	92	306	.40
	112	317	.54
	182	356	1.90
	[c]225	380	1.55
	[d]232	384	1.72
	[e]350	450	2.05
	[f]361	456	1.91
	[g]443	501	2.20
	[h]500	533	2.15
Filled epoxy in honeycomb (Avcoat 5026-39-HC G); direction B (Melpar)	[a]-200	144	-4.20
	-71	216	-2.63
	-15	247	-1.61
	50	283	-.25
	75	297	.00
	105	314	.47
	190	361	1.65
	[b]-82	210	-2.74
	-50	228	-2.01
	55	286	-.40
	75	297	.00
	125	325	.75
	202	367	1.53
	[c]340	444	1.88
	[d]355	452	1.95
	[e]460	511	2.11
	[f]490	527	2.08
Filled epoxy in honeycomb (Avcoat 5026-39-HC G); direction C (Melpar)	[a]-174	159	-4.04
	-83	209	-2.81
	20	266	-.95
	75	297	.00
	112	317	.91
	[b]-173	159	-4.02
	-61	221	-2.53
	35	275	-.90
	75	297	.00
	130	327	1.10
	[c]210	372	1.81
	[d]240	389	2.08
	[e]302	423	2.36
	[f]305	424	2.20
	[g]433	496	2.32
	[h]509	538	2.14

[a]Specimen 1.
[b]Specimen 2.
[c]Specimen 3.
[d]Specimen 4.
[e]Specimen 5.
[f]Specimen 6.
[g]Specimen 7.
[h]Specimen 8.
[i]Specimen 9.
[j]Specimen 10.
[k]Specimen 11.
[l]Specimen 12.
[m]Specimen 13.

TABLE 5.- EMITTANCE OF PHENOLIC-NYLON CHARS (SRI)

Ablation material	Specimen	Observed temperature, °F	Observed temperature, °K	True temperature, °F	True temperature, °K	Total normal emittance
High-density phenolic-nylon char	[a]1	1410	1038	1495	1085	0.67
		1489	1082	1574	1129	.77
		1606	1147	1708	1203	.75
		1809	1259	1922	1322	.86
		2200	1476	2367	1569	.84
		2360	1565	2538	1664	.87
		2532	1661	2735	1773	.86
		2679	1742	2939	1886	.74
		2861	1843	3188	2025	.65
		2919	1875	3270	2070	.62
		2919	1875	3190	2026	[b].81
	[c]3	1595	1141	1676	1185	.93
		1889	1304	2008	1370	.89
		2200	1476	2367	1569	.83
		2553	1672	2770	1793	.79
		2819	1820	3134	1995	.66
		2840	1832	3109	1981	.78
		2970	1904	3335	2106	.62
		3000	1920	3371	2126	[b].62
	[c]4	1578	1131	1674	1184	.77
		2050	1393	2193	1470	.86
		2388	1581	2578	1686	.84
		2741	1777	2963	1900	.89
		3172	2016	3437	2163	.91
		3740	2331	4146	2556	[b].79
	[c]5	1409	1037	1441	1055	.75
		1648	1170	1628	1159	.90
		2032	1383	2192	1472	.75
		2359	1565	2570	1682	.74
		2591	1693	2840	1832	.73
		2814	1817	3083	1966	.77
		3180	2020	3513	2205	.76
		3398	2141	3768	2347	.75
		3516	2207	3881	2409	[b].80

[a]Specimen appeared to be transmitting some subsurface radiation from heating disks.

[b]Heating disks melted.

[c]Thermatomic carbon used to fill cracks and reduce subsurface radiation.

TABLE 5.- EMITTANCE OF PHENOLIC-NYLON CHARS (SRI) - Concluded

Ablation material	Specimen	Observed temperature		True temperature		Total normal emittance
		°F	°K	°F	°K	
Low-density phenolic-nylon char	1	1490	1082	1573	1128	0.79
		1528	1103	1608	1148	.86
		1890	1304	2013	1373	.86
		1887	1303	2012	1372	.85
		2317	1541	2498	1642	.84
		2295	1529	2460	1621	.90
		3270	2070	3565	2234	.87
	2	1400	1032	1468	1070	.83
		1549	1115	1629	1159	.89
		1538	1109	1620	1154	.86
		1761	1233	1866	1291	.88
		1788	1248	1899	1309	.86
		1900	1310	2010	1371	.96
		2070	1149	2207	1480	.91
		2332	1550	2493	1639	.94
		2322	1544	2479	1631	.96
		2535	1662	2716	1763	.95
		2710	1759	2948	1891	[d].82
		2866	1846	3166	2012	[d].71
		2845	1834	3126	1990	[d].75
		2990	1915	3323	2100	[d].68
	3	1673	1184	1764	1234	.92
		1935	1329	2058	1397	.90
		2140	1443	2280	1521	.94
		2419	1598	2584	1689	.97
		2595	1696	2812	1816	[d].84
		2937	1885	3237	2052	[d].74
	4	1596	1141	1680	1188	.90
		1792	1250	1907	1314	.84
		1941	1333	2068	1403	.88
		2295	1529	2451	1616	.95
		2295	1529	2457	1619	.92
		2575	1684	2769	1792	.92
	5	3480	2187	3786	2357	.91
		3540	2220	3861	2398	.89

[d]White residue formed on surface.

TABLE 6.- DENSITY OF SIX CHARRING ABLATORS AND TWO CHARS

Ablation material	Temperature		Density	
	$^{\circ}$F	$^{\circ}$K	lb/ft^3	kg/m^3
			(a)	
High-density phenolic-nylon (Melpar)	-200	144	73.35	1175
	-100	200	72.92	1168
	0	255	72.36	1159
	32	273	72.17	1156
	[b]75	297	71.79	1150
	104	313	70.86	1135
	212	373	68.99	1105
	284	413	67.30	1078
	320	433	66.74	1069
	356	453	65.80	1054
	374	463	65.30	1046
			(a)	
Low-density phenolic-nylon (Melpar)	-200	144	37.53	601.2
	-103	198	37.31	597.7
	-4	251	37.08	593.9
	32	273	36.98	592.3
	[b]75	297	36.83	590.0
	104	313	36.39	582.9
	212	373	35.73	572.4
	284	413	35.14	562.8
	320	433	34.97	560.2
	387	470	34.36	550.4
			(c)	
Low-density phenolic-nylon (SRI)	-200	144	37.25	596.6
	-100	200	37.03	593.1
	0	255	36.78	589.1
	[b]70	294	36.56	585.6
	100	311	36.48	584.4
	150	339	36.33	582.0
			(a)	
Filled silicone resin (Melpar)	-222	132	42.58	682.1
	-155	169	42.05	673.5
	0	255	40.64	651.0
	32	273	40.38	646.8
	[b]75	297	39.96	640.0
	133	329	39.34	630.1
	154	341	39.12	626.6
	251	395	38.34	614.1
	324	435	37.68	603.5
	387	470	37.21	596.1
			(c)	
Filled silicone resin (SRI)	-200	144	41.80	669.5
	-100	200	41.19	659.8
	0	255	40.31	645.7
	[b]70	294	39.66	635.3
	100	311	39.44	631.7
	150	339	-----	-------
	200	366	38.61	618.4
	300	422	37.74	604.5
	400	478	36.84	590.1
			(a)	
Filled silicone resin in honeycomb (Melpar)	-200	144	43.39	702.7
	-119	189	43.16	691.4
	0	255	42.36	678.6
	32	273	42.17	675.5
	[b]75	297	41.83	670.0
	151	339	41.14	658.9
	248	393	40.42	647.4
	342	445	39.59	634.1
	420	488	39.19	627.8
			(a)	
Carbon-fiber-reinforced phenolic (Narmco 4028) (Melpar)	-225	130	87.46	1401
	-143	176	87.28	1398
	-40	233	87.09	1395
	5	258	86.97	1393
	[b]75	297	86.78	1390
	95	308	86.72	1389
	226	381	86.09	1379
	363	457	85.34	1367
	437	498	84.41	1352
	539	554	80.47	1289
	648	615	77.60	1243
	750	672	75.17	1204
			(a)	
Filled epoxy in honeycomb (Avcoat 5026-39-HC G) (Melpar)	-174	159	33.52	536.9
	-82	210	33.39	534.9
	0	255	33.26	532.8
	32	273	33.19	531.6
	[b]75	297	33.09	530.0
	125	325	32.65	523.0
	210	372	32.14	514.8
	340	444	31.14	498.8
	443	501	29.98	480.2
	500	532	29.20	467.7

[a]Density calculated from thermal-expansion data and weight measurements after exposure to temperature.
[b]Room-temperature measurement.
[c]Density calculated from thermal-expansion data and room-temperature density measurements.

TABLE 7.- TENSILE PROPERTIES OF SIX CHARRING ABLATORS (MELPAR)

Ablation material	Temperature		Ultimate strength		Young's modulus		Yield strength at 0.2% offset		Total elongation, %	Poisson's ratio
	°F	°K	psi	MN/m²	ksi	GN/m²	psi	MN/m²		
High-density phenolic-nylon	-200	144	2730	18.8	789.0	5.44			0.43	
	-200	144	2750	19.0	629.0	4.34			.38	
	-100	200	2940	20.3	715.0	4.93			.40	
	-100	200	3210	22.1	682.0	4.70			.50	
	0	255	2060	14.2	655.0	4.52			.4	
	0	255	2330	16.1	641.8	4.43			.3	
	75	297	2246	15.49	428.0	2.95			.6	
	75	297	2675	18.44	445.0	3.07			.6	
	200	366	1990	13.7	151.0	1.04			.9	
	200	366	2060	14.2	147.0	1.01			.9	
	300	422	1390	9.58	80.25	.55			1.5	
	300	422	1122	7.74	66.75	.46			1.8	
	350	450	578	3.99	56.00	.38			1.6	
	350	450	429	2.96	56.10	.38			1.6	
	400	477	267	1.84	22.80	.15			2.4	
	400	477	358	2.47						
	500	533	92	.63	10.50	.72				
Low-density phenolic-nylon	-200	144	760	5.24	288.0	1.986			.60	
	-200	144	715	4.92	240.0	1.655			1.04	
	-100	200	1170	8.07	137.5	.9481			.74	
	-100	200	1190	8.21	172.4	1.189			.90	
	0	255	1240	8.55	128.4	.8853			1.05	
	0	255	1260	8.69	120.3	.8295			1.14	
	75	297	1130	7.79	113.7	.7840			.70	
	75	297	890	6.14	133.0	.917			1.08	
	200	366	898	6.19	72.20	.498			1.2	
	200	366	1112	7.67	88.00	.607			1.1	
	300	422	880	6.07	50.50	.348			2.3	
	300	422	951	6.56	47.00	.324			1.4	
	350	450	668	4.61	41.00	.283			2.1	
	350	450	663	4.57	43.10	.297				
	400	477	390	2.69	30.75	.2120			1.00	
	400	477	278	1.92	26.60	.183			1.04	
Filled silicone resin	-200	144	2640	18.2	330.0	2.27	2425	16.72	1.1	
	-200	144	2130	14.7	304.0	2.10	2106	14.52	.9	
	-100	200	310	2.14	51.0	.35	277	1.91	.9	
	-100	200	320	2.21	51.0	.35	181	1.25	2.2	
	0	255	122	.841	5.3	.037	69	.48	3.6	
	0	255	117	.807	5.3	.037	64	.44	3.6	
	75	297	[a]75.2	.519	2.4	.017	50.7	.350	[b]>3.6	0.36
	75	297	[a]79.5	.548	2.5	.017	48.0	.331	[b]>3.6	.42
	200	366	[a]81.1	.559	2.4	.017	29.3	.202	[b]>3.6	.42
	200	366	[a]101.3	.6985	2.4	.017	34.7	.239	[b]>3.6	.42
	300	422	[a]103.5	.7136	2.0	.014	62.9	.434	[b]>3.6	.41
	300	422	[a]104	.717	2.5	.017	40	.28	[b]>3.6	
	400	477	[a]50.7	.350	1.3	.009	8	.05	[b]>3.6	
	400	477	69.3	.478	2.0	.014			3.4	
	[c]500	533								
	[c]500	533								
Filled silicone resin in honeycomb; direction A	-200	144	790	5.45	264.0	1.82			.2	
	-200	144	750	5.17	363.0	2.50			.3	
	-100	200	270	1.86	12.0	.827			3.5	
	-100	200	320	2.21	12.0	.827			3.6	
	0	255	245	1.69	11.5	.793			3.6	
	0	255	261	1.80	13.2	.910			3.6	
	75	297	[a]200	1.38	5.50	.38	74.7	.515	[b]>3.6	
	75	297	174	1.20	5.90	.41	112	.772	3.6	
	200	366	[a]154	1.06	4.80	.33			[b]>3.6	
	200	366	[a]155	1.07	5.30	.37	91.7	.632	[b]>3.6	
	300	422	[a]228	1.57	5.80	.40	136	.937	[b]>3.6	
	300	422	[a]232	1.60	5.50	.38	154	1.05	[b]>3.6	
	400	477	[a]135	.931	1.70	.12	42.7	.294	[b]>3.6	
	400	477	[a]105	.724	1.85	.128			[b]>3.6	
	500	533	[a]42.6	.294	2.00	.138	16	.110	[b]>3.6	
	500	533	[a]40.5	.279					[b]>3.6	

[a]Maximum stress.
[b]Strain not recorded beyond 3.6%.
[c]Specimen broke in grips.

TABLE 7.- TENSILE PROPERTIES OF SIX CHARRING ABLATORS (MELPAR) - Concluded

Ablation material	Temperature		Ultimate strength		Young's modulus		Yield strength at 0.2% offset		Total elongation, %	Poisson's ratio
	°F	°K	psi	MN/m²	ksi	GN/m²	psi	MN/m²		
Filled silicone resin in honeycomb; direction B	-200	144	880	6.1	272	1.88			0.6	
	-200	144	920	6.3	360	2.48			.3	
	-100	200	390	2.7	51	.35			1.44	
	-100	200	320	2.2	44	.30			1.7	
	0	255	155	1.07	9.25	.0638			3.6	
	0	255	160	1.1	10	.0690			3.6	
	75	297	[a]105	.724	4.5	.031	45.3	0.312	[b]>3.6	
	75	297	104	.696	4.5	.031	34.7	.239	3.6	
	200	366	72.5	.500	3.6	.025			2.4	
	200	366	101	.696	3.3	.023	56	.386	3.6	
	300	422	[a]120	.827	3.7	.026	85.3	.588	[b]>3.6	
	300	422	[a]104	.717	3.2	.022			[b]>3.6	
	400	477	55.5	.383	2.4	.017			2.8	
	400	477	62.9	.434	3.1	.021			2.6	
	[c]500	533								
Carbon-fiber-reinforced phenolic (Narmco 4028)	-200	144	4690	32.3	2350	16.2			.22	0.26
	-200	144	4380	30.2	2060	14.2			.23	.28
	-100	200	4450	30.7	2100	14.5			.23	.27
	-100	200	3540	24.4	1980	13.7			.18	.30
	0	255	3830	26.4	1810	12.5			.24	.26
	0	255	3810	26.3	1390	9.58			.28	.27
	75	297	4360	30.1	1480	10.2			.31	.31
	75	297	4920	33.9	1620	11.2			.31	.28
	200	366	2070	14.3	1300	8.96			.20	.34
	200	366	3910	27.0	1380	9.52			.30	.38
	300	422	3640	25.1	1280	8.83			.30	.18
	300	422	4010	27.6	1220	8.41			.31	.15
	400	477	2610	18.0	760	5.2			.33	.17
	400	477	2180	15.0	770	5.3			.24	.29
	500	533	1630	11.2	310	2.1			.92	.19
	500	533	1340	9.24	310	2.1			.94	.17
	600	588	1880	13.0	213	1.47			1.06	
	600	588	1770	12.2	211	1.45			1.07	
	700	644	1880	13.0	200	1.4			1.38	
	700	644	1620	11.2	270	1.9			.72	
	750	671	1260	8.69	238	1.64			.75	
	750	671	1485	10.24	250	1.7			.65	
Filled epoxy in honeycomb (Avcoat 5026-39-HC G); direction A	-200	144	747	5.15	198	1.37			.34	
	-200	144	629	4.34	207	1.43			.30	
	-100	200	677	4.67	130	.90			.52	
	-100	200	485	3.34	130	.90			.37	
	0	255	619	4.27	110	.76			.58	
	0	255	608	4.19	100	.69			.61	
	75	297	597	4.12	70	.48			.96	
	75	297	496	3.42	87	.60			.64	
	200	366	93	.64	22	.15			.41	
	200	366	120	.827	24	.17			.60	
	300	422	68	.47	22	.15			.31	
	300	422	86	.59	21	.14			.42	
	400	477	76	.52	23	.16			.32	
	400	477	53	.37	18	.12			.33	
Filled epoxy in honeycomb (Avcoat 5026-39-HC G); direction B	-200	144	549	3.79	140	.965			.32	
	-200	144	592	4.08	158	1.09			.39	
	-100	200	534	3.68	93	.641			.54	
	-100	200	496	3.42	110	.758			.47	
	0	255	448	3.09	95	.655			.44	
	0	255	491	3.39	91	.627			.57	
	75	297	496	3.42	59	.407			.92	
	75	297	362	2.50	55	.379			.68	
	200	366	49	.34	17	.119			.34	
	200	366	64	.44	13	.091			.52	
	300	422	49	.34	16	.110			.33	
	300	422	52	.36	13	.090			.42	
	400	477	20	.14	13	.090			.12	
	400	477	19	.13	13	.090			.12	

[a]Maximum stress.

[b]Strain not recorded beyond 3.6%.

[c]Specimen broke in grips.

TABLE 8.- TENSILE PROPERTIES OF LOW-DENSITY PHENOLIC-NYLON (SRI)

Temperature		Stress		Axial strain	Lateral strain	Poisson's ratio	Young's modulus		Yield strength at 0.2% offset		Ultimate strength		Total elongation, %	Load time to rupture, s
°F	°K	psi	MN/m²				ksi	GN/m²	psi	MN/m²	ksi	MN/m²		
-200	144	300	2.06	0.0012	0.0000	0.00	250	1.72	1400	9.653	1.400	9.653	0.56	330
		620	4.27	.0024	.0000	.00								
		1000	6.89	.0040	.0000	.00								
		1400	9.65	.0056	.0001	.02								
-200	144	350	2.41	.0021	.0000	.00	170	1.17	1430	9.860	1.430	9.860	.87	390
		700	4.82	.0044	.0000	.00								
		1060	7.30	.0065	.0001	.02								
		1430	9.860	.0087	.0001	.01								
-200	144	164	1.13	.0011	.0000	.00	159	1.09	880	6.06	.880	6.06	.59	240
		412	2.84	.0025	.0000	.00								
		668	4.60	.0044	.0000	.00								
		880	6.06	.0059	.0000	.00								
-100	200	340	2.34	.0021	.0006	.29	160	1.10	1300	8.964	1.300	8.964	.87	270
		710	4.89	.0043	.0010	.23								
		1030	7.102	.0066	.0014	.21								
		1300	8.964	.0087	.0018	.21								
-100	200	350	2.41	.0022	.0003	.14	150	1.02	1020	7.033	1.020	7.033	.77	240
		590	4.06	.0038	.0005	.13								
		830	5.72	.0060	.0008	.13								
		1020	7.033	.0077	.0010	.13								
0	255	310	2.13	.0027	.0002	.07	110	.758	1100	7.584	1.100	7.584	.99	300
		570	3.93	.0050	.0003	.06								
		860	5.93	.0077	.0005	.07								
		1100	7.584	.0099	.0007	.07								
0	255	400	2.75	.0026	.0010	.38	150	1.03	1180	8.136	1.180	8.136	.83	300
		660	4.55	.0045	.0020	.44								
		960	6.61	.0066	.0029	.44								
		1180	8.136	.0083	.0036	.42								
0	255	148	1.02	.0012	(a)	(b)	135	.931	1100	7.584	1.100	7.584	.93	210
		398	2.74	.0033										
		898	6.19	.0074										
		1100	7.584	.0093										
0	255	300	2.06	.0023	(a)	(b)	137	.945	1620	11.17	1.620	11.17	1.18	240
		800	5.51	.0059										
		1300	8.964	.0094										
		[c]1620	11.17	.0118										
70	294	92.5	.638	.0010	(a)	(b)	99	.68	1120	7.722	1.120	7.722	1.14	180
		437	3.01	.0046										
		785	5.41	.0079										
		1120	7.722	.0114										
70	294	208	1.43	.0015	(a)	(b)	120	.827	1310	9.032	1.310	9.032	(d)	210
		358	2.46	.0029										
		483	3.33	.0042										
		754	5.19	[d].0074										
70	294	460	3.17	.0047	.0014	.31	100	.670	1350	9.308	1.350	9.308	1.50	240
		780	5.37	.0080	.0024	.30								
		1090	7.516	.0117	.0033	.28								
		1350	9.308	.0150	.0043	.29								
70	294	510	3.51	.0039	.0009	.23	140	.965	1680	11.58	1.680	11.58	1.33	240
		910	6.27	.0069	.0017	.24								
		1300	8.964	.0102	.0024	.23								
		1680	11.58	.0133	.0032	.24								
150	339	450	3.10	.0076	.0012	.16	61	.42	1050	7.240	1.050	7.240	1.90	330
		650	4.48	.0108	.0020	.18								
		870	5.99	.0151	.0031	.21								
		1050	7.240	.0190	.0044	.23								
150	339	510	3.51	.0065	.0019	.29	83	.57	1240	8.550	1.440	9.929	2.19	360
		850	5.86	.0114	.0033	.28								
		1170	8.067	.0169	.0041	.24								
		1440	9.929	.0219	.0047	.22								

[a]Lateral strain not monitored.

[b]Indeterminate.

[c]Specimen dried for 15 hours at 200° F (366° K).

[d]Clip-on extensometer slipped off after strain of 0.0074.

TABLE 8.- TENSILE PROPERTIES OF LOW-DENSITY PHENOLIC-NYLON (SRI) - Concluded

Temperature, °F	Temperature, °K	Stress, psi	Stress, MN/m²	Axial strain	Lateral strain	Poisson's ratio	Young's modulus, psi	Young's modulus, GN/m²	Yield strength at 0.2% offset, ksi	Yield strength at 0.2% offset, MN/m²	Ultimate strength, ksi	Ultimate strength, MN/m²	Total elongation, %	Load time to rupture, s
250	394	270	1.86	0.0065	0.0028	0.43	43	0.29	400	2.75	0.680	4.68	4.41	420
		500	3.44	.0183	.0053	.29								
		560	3.86	.0253	.0064	.25								
		620	4.27	.0343	.0078	.23								
		680	4.68	.0441	.0090	.20								
250	394	260	1.79	.0090	.0024	.26	28	.19	390	2.68	.670	4.62	5.10	450
		400	2.75	.0174	.0043	.25								
		540	3.72	.0292	.0061	.21								
		620	4.27	.0406	.0077	.19								
		670	4.62	.0510	.0090	.18								
250	394	430	2.96	.0104	.0028	.26	41	.28	920	6.34	1.010	6.964	2.86	270
		660	4.55	.0158	.0043	.27								
		840	5.79	.0214	.0057	.27								
		1010	6.964	.0286	.0074	.26								
350	450	120	.827	.0088	.0010	.11	14	.096	210	1.44	.275	1.89	4.58	240
		200	1.37	.0177	.0019	.11								
		250	1.72	.0307	.0033	.11								
		275	1.89	.0458	.0049	.11								
350	450	190	1.31	.0169	.0017	.098	11	.075	320	2.20	.320	2.20	7.47	210
		270	1.86	.0293	.0026	.090								
		300	2.06	.0501	.0041	.081								
		320	2.20	.0747	.0054	.072								
450	505	88	.60	.0521	.0128	.25	1.8	.012	146	1.00	.146	1.00	9.24	150
		104	.717	.0618	.0171	.28								
		126	.869	.0744	.0229	.31								
		146	1.00	.0924	.0296	.32								
450	505	82	.56	.0386	.0039	.10	2.3	.015	82	.56	.150	1.03	11.19	240
		118	.814	.0585	.0058	.10								
		132	.910	.0787	.0082	.10								
		150	1.03	.1119	.0156	.14								
450	505	58	.40	.0410	.0018	.043	1.4	.0096	70	.48	.150	1.03	13.83	240
		98	.67	.0714	.0030	.042								
		120	.827	.1043	.0047	.045								
		150	1.03	.1383	.0066	.047								
450	505	14	.096	.0026	.0007	.27	3.8	.026	146	1.00	.146	1.00	3.56	180
		54	.37	.0119	.0037	.31								
		92	.63	.0246	.0061	.25								
		146	1.00	.0356	.0087	.24								
450	505	54	.37	.0152	.0064	.42	3.6	.024	150	1.03	.150	1.03	4.27	270
		90	.62	.0243	.0125	.52								
		122	.841	.0334	.0198	.59								
		150	1.03	.0427	.0299	.70								
500	533	56	.38	.0222	.0124	.56	2.5	.017	63	.43	.164	1.13	10.78	300
		95	.65	.0532	.0222	.42								
		131	.903	.0815	.0325	.40								
		164	1.13	.1078	.0432	.40								
550	561	60	.41	.0109	.0078	.72	5.4	.037	86	.59	.146	1.00	4.67	210
		98	.67	.0208	.0160	.77								
		122	.84	.0316	.0285	.90								
		146	1.00	.0467	.0426	.91								
550	561	51	.35	.0178	.0173	.97	2.8	.019	126	.869	.126	.869	4.80	210
		74	.51	.0261	.0303	1.16								
		102	.703	.0371	.0537	1.45								
		126	.869	.0480	.0737	1.54								
650	616	22	.15	.0094	.0261	2.79	2.3	.015	51	.35	.063	.43	3.18	330
		39	.26	.0169	.0343	2.03								
		54	.37	.0254	.0463	1.82								
		63	.43	.0318	.0577	1.81								
700	644	17	.11	------	------	----	(b)	------	(b)	-----	.017	.11	(e)	120
750	672	15	.10	------	------	----	(b)	------	(b)	-----	.015	.10	(f)	180

[b]Indeterminate.

[e]Extensometer slipped off after strain of 0.085.

[f]Extensometer slipped off after strain of 0.070.

TABLE 9.- TENSILE PROPERTIES OF FILLED SILICONE RESIN (SRI)

Temperature		Stress		Axial strain	Lateral strain	Poisson's ratio	Young's modulus		Yield strength at 0.2% offset		Ultimate strength		Total elongation, %	Load time to rupture, s
°F	°K	psi	MN/m²				ksi	MN/m²	psi	MN/m²	psi	MN/m²		
-200	144	135	0.931	0.0002	[a]0	0	976	6730	976	6.73	(b)	------	0.001	150
		338	2.33	.0004	0	0								
		585	4.03	.0007	0	0								
		[b]888	6.12	.0010	0	0								
-200	144	681	4.69	.0005	[a]0	0	1700	11720	2120	14.61	2170	14.96	.005	180
		1720	11.85	.0012	0	0								
		2170	14.96	.0034	0	0								
		1880	12.96	.0049	0	0								
-200	144	[c]2130	14.68	------	-------	----	(c)	--------	(d)	------	2130	14.68	(c)	180
-200	144	113	.779	.0001	0	0	1110	7653	(d)	------	(b)	------	[b,c].03	330
		199	1.37	.0002	0	0								
		334	2.30	[c].0003	0	0								
		517	3.56	------	0	0								
		[b]777	5.35	------	.0001	0								
-150	172	102	.703	.0032	0	0	32	220	190	1.31	(e)	(e)	[e]2.15	420
		162	1.11	.0063	.0002	.03								
		212	1.46	.0109	.0003	.03								
		[e]252	1.73	.0215	.0005	.02								
-150	172	78	.53	.0030	.0001	.03	26	180	175	1.21	(b)	(b)	[b]2.40	180
		152	1.04	.0066	.0003	.05								
		204	1.40	.0124	.0006	.05								
		[b]260	1.79	.0240	.0012	.05								
-100	200	32	.22	.0087	.0044	.51	3.6	25	54	.37	156	1.08	13.0	330
		75	.51	.0279	.0106	.38								
		114	.78	.0568	.0186	.33								
		136	.938	.0938	.0264	.28								
		156	1.08	.1300	.0310	.24								
-100	200	53	.36	.0145	.0044	.30	3.7	25	90	.62	165	1.14	15.3	360
		110	.758	.0354	.0122	.34								
		147	1.01	.0787	.0244	.31								
		165	1.14	.1528	.0561	.37								
0	255	23	.16	.0160	.0038	.24	1.4	9.7	40	.28	(e)	------	[c,e]11.5	330
		42	.29	.0344	.0079	.23								
		64	.44	.0652	.0117	.18								
		77	.53	[c].1145	.0159	.14								
		[e]91	.63	(d)	.0530	(d)								
0	255	28	.19	.0164	.0088	.53	1.7	12	30	.21	93	.64	17.5	390
		53	.36	.0522	.0186	.36								
		64	.44	.1132	.0266	.23								
		69	.48	[c].1750	.0326	.19								
		93	.64	(d)	.0810	(d)								
0	255	26	.18	.0086	(f)	(f)	2.7	19	40	.28	157	1.08	33.0	480
		74	.51	.0402	-------	----								
		117	.807	.1550	-------	----								
		157	1.08	.3300	-------	----								
70	294	30	.21	.0200	.0110	.55	1.85	12.8	31	.21	71	.49	14.3	180
		51	.35	.0620	.0271	.44								
		59	.41	.1052	.0441	.42								
		71	.49	.1432	.0583	.41								
70	294	30	.21	.0193	.0114	.59	1.59	11.0	34	.23	63	.43	13.4	240
		49	.34	.0490	.0260	.53								
		62	.43	.0903	.0440	.49								
		63	.43	.1340	.0539	.40								

[a]No lateral strain detected.

[b]Specimen broke in grips.

[c]Clip-on extensometer slipped off.

[d]Indeterminate.

[e]Specimen slipped out of grips before rupture.

[f]Lateral strain not monitored.

TABLE 9.- TENSILE PROPERTIES OF FILLED SILICONE RESIN (SRI) - Concluded

Temperature		Stress		Axial strain	Lateral strain	Poisson's ratio	Young's modulus		Yield strength at 0.2% offset		Ultimate strength		Total elongation, %	Load time to rupture, s
°F	°K	psi	MN/m²				ksi	MN/m²	psi	MN/m²	psi	MN/m²		
150	339	43	0.30	0.0441	0.0298	0.67	1.00	6.90	45	0.31	75	0.52	18.8	420
		60	.41	.0925	.0522	.56								
		70	.48	.1425	.0721	.51								
		75	.52	.1882	.0888	.47								
150	339	33	.24	.0344	.0292	.85	1.08	7.45	29	.20	67	.46	20.9	480
		52	.36	.0965	.0648	.67								
		62	.43	.1620	.0982	.61								
		67	.46	.2090	.1223	.58								
250	394	29	.20	.0483	.0346	.71	.63	4.3	30	.21	47	.32	17.8	360
		40	.28	.0812	.0473	.58								
		46	.32	.1269	.0655	.52								
		47	.32	.1782	.0791	.44								
250	394	30	.21	.0230	.0122	.53	1.50	10.3	35	.24	68	.47	17.4	330
		52	.36	.0652	.0234	.36								
		62	.43	.1069	.0311	.29								
		68	.47	.1737	.0376	.22								
350	450	26	.18	.0243	.0067	.28	1.13	7.79	31	.21	54	.37	11.5	300
		40	.28	.0483	.0102	.21								
		49	.34	.0787	.0133	.17								
		54	.37	.1152	.0168	.15								
350	450	16	.11	.0274	.0142	.52	.62	4.3	17	.12	45	.31	9.7	300
		25	.17	.0492	.0217	.44								
		34	.23	.0702	.0312	.44								
		45	.31	.0967	.0401	.42								
450	505	17	.12	.0413	.0105	.25	.46	3.2	18	.12	45	.31	14.5	330
		28	.19	.0854	.0193	.23								
		38	.26	.1161	.0283	.24								
		45	.31	.1447	.0394	.27								
450	505	10	.69	.0307	.0201	.65	.35	2.4	12	.083	26	.18	11.0	240
		17	.12	.0632	.0295	.47								
		22	.15	.0836	.0379	.45								
		26	.18	.1104	.0481	.43								
550	561	8.1	.056	------	(g)	----	----	----	--	-----	8.1	.056	----	---
650	616	5.3	.037	------	(g)	----	----	----	--	-----	5.3	.037	----	---

[g]Calibration specimen.

TABLE 10.- COMPRESSIVE PROPERTIES OF SIX CHARRING ABLATORS (MELPAR)

Ablation material	Temperature		Ultimate strength		Young's modulus		Yield strength at 0.2% offset		Total compression, %
	°F	°K	ksi	MN/m^2	ksi	GN/m^2	ksi	MN/m^2	
High-density phenolic-nylon	-200	144	36.04	248.5	860	5.93	19.20	132	4.5
	-200	144	33.20	228.9	900.0	6.21	------	-------	6.6
	-100	200	27.20	187.5	910.0	6.27	18.88	130	5.0
	-100	200	28.48	196.4	730.0	5.03	18.40	127	4.6
	0	255	[a]26.88	185.3	715.0	4.93	15.60	108	[b]>7.2
	0	255	30.00	206.8	705.0	4.86	18.80	130	5.6
	75	297	[a]21.20	146.2	605.0	4.17	9.08	62.6	[b]>7.2
	75	297	[a]19.60	135.1	460.0	3.17	11.30	77.9	[b]>7.2
	200	366	12.04	83.02	195.5	1.35	3.82	26.3	7.2
	200	366	[a]15.02	103.6	238.0	1.64	4.76	32.8	[b]>7.2
	300	422	[a]5.52	38.1	80.0	.55	1.76	12.1	[b]>7.2
	300	422	[a]5.20	35.9	78.0	.54	1.60	11.0	[b]>7.2
	400	477	[a]2.32	16.0	30.0	.21	1.20	8.2	[b]>7.2
	400	477	[a]2.60	17.9	30.0	.21	.92	6.3	[b]>7.2
Low-density phenolic-nylon	-200	144	5.000	34.5	242.0	1.66	------	-------	2.2
	-200	144	5.240	36.1	184.0	1.27	------	-------	3.0
	-100	200	4.010	27.6	189.0	1.30	2.750	19.0	2.7
	-100	200	3.540	24.4	136.0	.938	3.040	21.0	2.8
	0	255	4.190	28.9	187.0	1.29	2.736	18.9	2.4
	0	255	3.680	25.4	219.0	1.51	2.560	17.7	3.0
	75	297	3.560	24.5	139.0	.958	2.448	16.9	4.0
	75	297	3.912	27.0	151.0	1.04	2.488	17.2	5.0
	200	366	[a]3.020	20.8	111.5	.769	1.080	7.45	[b]>7.2
	200	366	2.670	18.4	128.0	.882	1.440	9.93	6.6
	300	422	[a]2.940	20.3	51.0	.350	1.400	9.65	[b]>7.2
	300	422	2.880	19.9	47.0	.320	1.320	9.10	------
	400	477	[a]2.490	17.2	33.3	.230	1.200	8.30	[b]>7.2
	400	477	[a]2.300	15.9	30.0	.210	1.040	7.17	[b]>7.2
Filled silicone resin	-200	144	[c].760	5.24	12.50	.0861	.300	2.10	40.4
	-200	144	[c]1.000	6.90	13.60	.0938	.440	3.00	44.4
	-100	200	[c].275	1.90	3.00	.0207	.144	.993	35.2
	-100	200	[c].235	1.62	3.10	.0214	.124	.855	29.8
	0	255	.212	1.46	2.20	.0152	.136	.938	20.6
	0	255	.204	1.41	2.50	.0172	.128	.883	17.0
	75	297	[c].280	1.93	2.10	.0145	.114	.786	70.8
	75	297	[c].270	1.86	2.20	.0152	.112	.772	68.4
	150	338	[c].275	1.90	2.30	.0159	.144	.993	59.4
	150	338	[c].260	1.79	2.10	.0145	.140	.965	61.2
	200	366	[c].210	1.45	2.00	.0138	.128	.883	55.4
	200	366	[c].225	1.55	2.40	.0165	.120	.827	59.0
	300	422	[c].272	1.88	2.30	.0159	.128	.883	35.0
	300	422	[c].220	1.72	2.00	.0138	.120	.827	34.4
	400	477	[c].176	1.21	3.00	.0207	.096	.662	31.8
	400	477	[c].168	1.16	2.60	.0179	.104	.717	30.0
	500	533	.172	1.19	.78	.0054	------	-------	19.6
	500	533	.196	1.35	.68	.0047	------	-------	17.4
	600	588	.078	.54	.31	.0021	------	-------	11.6
	600	588	.100	.69	.29	.0020	------	-------	17.8
	700	644	.027	.19	.20	.0014	------	-------	20.0
Filled silicone resin in honeycomb; direction A	-200	144	[c].960	6.62	10.00	.069	.540	3.7	21.8
	-200	144	.832	5.74	14.00	.097	.400	2.8	23.0
	-100	200	[c].348	2.40	3.80	.026	.140	.97	41.0
	-100	200	[c].386	2.66	4.20	.029	.160	1.1	26.8
	0	255	[c].300	2.07	4.20	.029	.176	1.21	28.6
	0	255	[c].310	2.14	4.00	.028	.168	1.16	25.4
	75	297	[c].285	1.97	3.50	.024	.152	1.05	32.8
	75	297	[c].296	2.04	3.60	.025	.152	1.05	28.6
	200	366	[c].306	2.11	3.80	.026	.160	1.10	28.4
	200	366	[c].311	2.14	3.80	.026	.160	1.10	25.8
	300	422	[c].267	1.84	3.00	.021	.184	1.27	22.4
	300	422	.276	1.90	3.10	.021	.160	1.10	21.0
	400	477	.216	1.49	2.50	.017	.152	1.05	14.0
	400	477	.228	1.57	2.80	.019	.128	.883	14.0
	500	533	.188	1.30	1.80	.012	.168	1.16	12.6
	500	533	.183	1.26	1.70	.012	.168	1.16	13.0
	600	588	.088	.61	.80	.0055	------	-------	11.0
	600	588	.090	.62	.74	.0051	------	-------	11.8
	700	644	.024	.16	.48	.0033	------	-------	6.2
	700	644	.028	.19	.39	.0027	------	-------	14.0

[a]Maximum stress.
[b]Strain not recorded beyond 7.2%.
[c]Stress at 20% strain.

TABLE 10.- COMPRESSIVE PROPERTIES OF SIX CHARRING ABLATORS (MELPAR) - Continued

Ablation material	Temperature		Ultimate strength		Young's modulus		Yield strength at 0.2% offset		Total compression, %
	°F	°K	ksi	MN/m²	ksi	GN/m²	ksi	MN/m²	
Filled silicone resin in honeycomb; direction B	-200	144	c0.750	5.17	9.50	0.065	0.360	2.5	31.0
	-200	144	c.710	4.90	8.00	.055	.280	1.9	50.0
	-100	200	c.375	2.59	3.50	.024	.176	1.21	43.0
	-100	200	c.335	2.31	4.20	.029	.200	1.37	35.6
	0	255	.272	1.88	3.60	.025	.136	.938	19.4
	0	255	.252	1.74	4.40	.030	.160	1.10	12.8
	75	297	c.325	2.24	3.10	.021	.152	1.05	46.2
	75	297	c.329	2.27	3.50	.024	.144	.992	41.2
	200	366	c.382	2.63	2.90	.020	.192	1.32	25.8
	200	366	c.360	2.48	3.80	.026	.152	1.05	35.6
	300	422	c.290	2.00	2.60	.018	.152	1.05	37.0
	300	422	c.307	2.12	3.10	.021	.152	1.05	38.4
	400	477	c.240	1.65	2.20	.015	.120	.827	25.4
	400	477	c.245	1.69	2.80	.019	.124	.855	24.0
	500	533	.204	1.41	1.40	.0097	------	-------	14.2
	500	533	.220	1.52	1.70	.0117	------	-------	15.0
	600	588	.122	.841	.33	.0023	------	-------	15.6
	600	588	.114	.786	.33	.0023	------	-------	18.4
	700	644	.064	.44	.20	.0014	------	-------	23.0
	700	644	.040	.28	.40	.0028	------	-------	9.8
Filled silicone resin in honeycomb; direction C	-200	144	1.900	13.10	57.0	.393	1.480	10.20	5.2
	-200	144	1.900	13.10	65.0	.448	1.420	9.79	5.0
	-100	200	.930	6.41	63.0	.434	.810	5.58	4.6
	-100	200	.820	5.65	58.0	.400	.710	4.90	3.6
	0	255	.800	5.52	40.3	.278	.665	4.59	3.4
	0	255	.735	5.07	35.6	.245	.570	3.93	3.6
	75	297	.728	5.02	35.5	.245	.720	4.96	3.0
	75	297	.780	5.38	41.0	.283	.740	5.70	2.4
	200	366	.790	5.45	44.0	.303	.730	5.03	2.3
	200	366	.685	4.72	35.0	.241	.650	4.48	2.2
	300	422	.783	5.40	41.5	.286	.775	5.34	2.2
	300	422	.795	5.48	50.0	.345	.785	5.41	2.0
	400	477	.735	5.07	32.0	.221	.705	4.86	2.8
	400	477	.690	4.76	37.0	.255	.675	4.65	2.3
	500	533	.395	2.72	35.0	.241	------	-------	1.3
	500	533	.410	2.83	30.0	.207	------	-------	1.6
	600	588	.270	1.86	21.8	.150	------	-------	1.2
	600	588	.250	1.72	24.0	.165	------	-------	1.2
	700	644	.305	2.10	39.0	.269	------	-------	.8
	700	644	.335	2.31	45.0	.290	------	-------	1.0
Carbon-fiber-reinforced phenolic (Narmco 4028)	-200	144	45.00	310	1830	12.6	------	-------	1.7
	-200	144	51.50	355	1700	11.7	------	-------	3.2
	-100	200	47.00	324	1380	9.52	------	-------	4.2
	-100	200	47.00	324	1580	10.9	------	-------	3.8
	0	255	41.00	283	1200	8.27	------	-------	4.8
	0	255	46.80	323	1600	11.0	------	-------	3.7
	75	297	48.80	336	1800	12.4	31.6	218	4.2
	75	297	51.30	354	1650	11.4	34.0	234	5.0
	200	366	40.00	276	1030	7.10	31.0	214	6.7
	200	366	40.50	279	910	6.30	31.5	217	7.6
	300	422	34.20	236	990	6.80	21.0	145	8.3
	300	422	32.20	222	900	6.20	21.0	145	8.1
	400	477	23.30	161	610	4.20	14.0	97.0	7.9
	400	477	24.00	165	580	4.00	14.0	97.0	8.7
	500	533	16.70	115	290	2.00	14.3	98.6	8.3
	500	533	18.00	124	330	2.30	13.1	90.3	8.7
	600	588	14.80	102	250	1.70	14.2	97.9	8.0
	600	588	15.60	108	250	1.70	14.7	101	8.6
	700	644	19.35	133	375	2.59	13.7	94.5	8.0
	700	644	18.50	128	320	2.20	15.6	108	8.2
	750	671	16.50	114	289	2.00	12.5	86.2	7.5
	750	671	15.20	105	275	1.90	12.6	86.9	7.3
Filled epoxy in honeycomb (Avcoat 5026-39/HC G); direction A	-200	144	1.960	13.5	61.0	.421	1.490	10.3	7.2
	-200	144	1.910	13.2	63.0	.434	1.500	10.3	4.8
	-100	200	1.280	8.83	85.0	.586	1.090	7.52	4.5
	-100	200	1.400	9.65	78.0	.538	1.100	7.58	5.2
	0	255	1.020	7.03	76.0	.524	.740	5.10	4.6
	0	255	.995	6.86	63.0	.434	.930	6.40	3.2
	75	297	1.110	7.65	87.0	.600	.930	6.40	3.0
	75	297	1.050	7.24	83.0	.572	.880	6.1	3.2
	200	366	.265	1.83	13.2	.091	.260	1.8	2.9
	200	366	.220	1.52	10.8	.074	.214	1.5	5.5
	300	422	.086	.59	8.0	.055	------	-------	2.5
	300	422	.162	1.12	10.8	.074	------	-------	1.9

[c] Stress at 20% strain.

TABLE 10.- COMPRESSIVE PROPERTIES OF SIX CHARRING ABLATORS (MELPAR) - Concluded

Ablation material	Temperature		Ultimate strength		Young's modulus		Yield strength at 0.2% offset		Total compression, %
	°F	°K	ksi	MN/m²	ksi	GN/m²	ksi	MN/m²	
Filled epoxy in honeycomb (Avcoat 5026-39/HC G); direction B	-200	144	2.000	13.8	53.0	0.365	1.280	8.83	10.5
	-200	144	1.790	12.3	58.0	.400	1.380	9.52	8.7
	-100	200	1.750	12.1	70.0	.483	1.180	8.14	10.2
	-100	200	1.430	9.86	68.0	.469	.800	5.51	8.2
	0	255	1.480	10.2	81.0	.558	1.030	7.10	5.9
	0	255	1.630	11.2	82.0	.565	1.060	7.31	6.7
	75	297	1.380	9.52	71.0	.490	.970	6.7	6.8
	75	297	1.270	8.76	72.0	.496	.930	6.4	6.0
	200	366	.400	2.80	9.40	.065	.284	1.96	12.0
	200	366	.316	2.18	8.80	.061	.230	1.59	9.9
	300	422	.324	2.23	8.00	.055	.260	1.79	6.0
	300	422	.280	1.90	6.60	.046	.248	1.71	5.2
	400	477	.214	1.48	7.20	.050	.204	1.41	4.1
	400	477	.254	1.75	8.60	.059	.226	1.56	3.8
Filled epoxy in honeycomb (Avcoat 5026-39/HC G); direction C	-200	144	2.270	15.7	122.5	.8446	------	------	3.4
	-200	144	2.300	15.9	114.0	.786	------	------	3.4
	-100	200	1.800	12.4	98.0	.676	------	------	2.9
	-100	200	1.525	10.5	89.5	.617	------	------	3.3
	0	255	1.610	11.1	83.5	.576	------	------	3.1
	0	255	1.770	12.2	82.0	.565	------	------	3.3
	75	297	1.650	11.4	86.0	.593	1.320	9.10	3.2
	75	297	1.600	11.0	90.0	.621	1.530	10.5	2.7
	115	319	.735	5.07	55.5	.383	.650	4.48	2.3
	115	319	.710	4.90	62.0	.427	.630	4.34	1.8
	150	338	.585	4.03	50.7	.350	.555	3.83	2.2
	200	366	.410	2.83	26.0	.179	.302	2.08	2.6
	200	366	.450	3.10	30.0	.207	.375	2.59	2.4
	300	422	.360	2.48	13.7	.0945	.340	2.34	3.0
	300	422	.390	2.69	16.9	.117	.376	2.59	3.0
	400	477	.420	2.90	27.2	.1875	.415	2.86	2.1
	400	477	.455	3.14	22.4	.154	.450	3.10	3.0
	450	505	.322	2.22	23.0	.159	.264	1.82	2.3
	450	505	.280	1.93	20.7	.143	.246	1.70	2.3
	500	533	.302	2.08	32.6	.225	.290	2.00	1.7
	500	533	.314	2.16	27.8	.192	.240	1.65	2.0
	600	588	.180	1.24	17.0	.117	.094	.65	2.0

TABLE 11.- COMPRESSIVE PROPERTIES OF LOW-DENSITY PHENOLIC-NYLON (SRI)

Temperature		Stress		Axial strain	Lateral strain	Poisson's ratio	Young's modulus		Yield strength at 0.2% offset		Ultimate strength		Total compression, %	Load time to rupture, s
°F	°K	ksi	MN/m²				ksi	MN/m²	psi	MN/m²	ksi	MN/m²		
-200	144	1.800	12.41	0.0053	0.0026	0.49	360	2480	6580	45.37	6.580	45.37	2.05	300
		3.480	24.00	.0100	.0042	.42								
		4.930	33.99	.0141	.0058	.41								
		6.580	45.37	.0205	.0080	.39								
-200	144	1.280	8.826	.0040	.0014	.35	310	2130	4630	31.92	4.650	32.06	1.90	330
		2.530	17.44	.0081	.0030	.37								
		3.730	25.72	.0124	.0047	.38								
		4.650	32.06	.0190	.0063	.33								
-100	200	1.580	10.89	.0061	.0022	.36	250	1720	4630	31.92	5.080	35.03	2.53	300
		3.050	21.03	.0120	.0041	.34								
		4.330	29.85	.0179	.0061	.34								
		5.080	35.03	.0253	.0078	.31								
-100	200	1.580	10.89	.0064	.0025	.39	240	1650	4750	32.75	5.450	37.58	2.98	300
		3.050	21.03	.0124	.0042	.34								
		4.430	30.55	.0193	.0059	.31								
		5.450	37.58	.0298	.0081	.27								
0	255	1.430	9.860	.0101	.0037	.37	140	965	3230	22.27	4.250	29.30	4.68	330
		2.350	16.20	.0178	.0056	.31								
		3.600	24.82	.0312	.0087	.28								
		4.250	29.30	.0457	.0110	.24								
		4.030	27.79	.0468	.0111	.24								
0	255	1.680	11.58	.0090	.0036	.40	180	1240	4070	28.06	5.380	37.09	4.58	330
		3.280	22.62	.0186	.0061	.33								
		4.780	32.96	.0315	.0091	.29								
		5.380	37.10	.0458	.0110	.24								
70	294	1.375	9.479	.0107	.0040	.37	130	896	2900	20.00	4.500	31.03	6.95	360
		2.630	18.13	.0244	.0061	.34								
		4.030	27.79	.0400	.0101	.25								
		4.500	31.03	.0643	.0137	.21								
		4.400	30.34	.0695	.0144	.21								
70	294	1.500	10.34	.0124	.0035	.28	120	827	2800	19.31	3.830	26.41	6.78	360
		2.450	16.89	.0219	.0056	.26								
		3.550	24.48	.0411	.0096	.23								
		3.830	26.41	.0617	.0123	.20								
		3.630	25.03	.0678	.0143	.21								
150	339	1.860	12.83	.0212	.0042	.20	89	610	2450	16.89	3.950	27.24	11.20	390
		2.860	19.72	.0377	.0077	.20								
		3.480	23.99	.0576	.0123	.21								
		3.740	25.79	.0815	.0154	.27								
		3.950	27.24	.1120	.0204	.25								
150	339	.900	6.21	.0106	.0018	.17	86	590	2900	20.00	3.500	24.13	7.95	300
		1.720	11.86	.0200	.0041	.20								
		2.560	17.65	.0309	.0064	.21								
		3.400	23.44	.0553	.0108	.20								
		3.500	24.13	.0795	.0147	.19								
250	394	.810	5.59	.0147	.0042	.28	56	380	1120	7.722	[a]3.080	21.24	23	1200
		1.550	10.69	.0294	.0073	.25								
		2.390	16.48	.0732	.0197	.27								
		2.800	19.31	.1460	.0366	.25								
		3.140	21.65	.2300	.0600	.26								
250	394	.920	6.34	.0165	.0026	.16	55	380	1748	12.05	3.100	21.37	16.4	1200
		1.630	11.24	.0301	.0061	.20								
		2.530	17.44	.0653	.0148	.23								
		2.800	19.31	.0945	.0216	.23								
		3.100	21.37	.1640	.0352	.22								
350	450	.795	5.48	.0153	.0072	.47	54	370	1175	8.102	[a]2.970	20.48	19.1	450
		1.382	9.529	.0294	.0115	.39								
		1.922	13.25	.0550	.0187	.34								
		2.330	16.06	.1061	.0334	.32								
		2.970	20.48	.1910	.0618	.32								
350	450	.667	4.60	.0171	.0063	.36	40	280	1020	7.033	[a]2.230	15.38	20	420
		1.150	7.929	.0318	.0106	.33								
		1.610	11.10	.0627	.0190	.30								
		1.905	13.14	.1105	.0335	.30								
		2.230	15.38	.1995	.0652	.33								

[a]Stress at 20% strain.

TABLE 11.- COMPRESSIVE PROPERTIES OF LOW-DENSITY PHENOLIC-NYLON (SRI) - Concluded

Temperature		Stress		Axial strain	Lateral strain	Poisson's ratio	Young's modulus		Yield strength at 0.2% offset		Ultimate strength		Total compression, %	Load time to rupture, s
°F	°K	ksi	MN/m²				ksi	MN/m²	psi	MN/m²	ksi	MN/m²		
450	505	0.605	4.17	0.0183	0.0048	0.26	32	220	1200	8.274	[a]1.725	11.89	20.0	300
		1.210	8.343	.0373	.0159	.43								
		1.440	9.93	.0712	.0350	.49								
		1.525	10.52	.1045	.0437	.42								
		1.723	11.88	.2000	.1065	.52								
450	505	.615	4.24	.0294	.0147	.50	21	140	350	2.41	[a]1.225	8.446	20	360
		.795	5.48	.0550	.0252	.46								
		.965	6.65	.0972	.0434	.45								
		1.072	7.391	.1435	.0640	.45								
		1.225	8.446	.2005	.0912	.46								
550	561	.113	.779	.0094	.0006	.07	12	83	131	.903	[a].420	2.90	20	540
		.220	1.52	.0303	.0024	.08								
		.343	2.36	.0815	.0113	.14								
		.420	2.90	.1325	.0225	.17								
		.420	2.90	.2005	.0400	.20								
550	561	.0775	.534	.0177	.0048	.27	4.4	30	158	1.09	[a].474	3.27	20	480
		.175	1.21	.0418	.0068	.16								
		.235	1.62	.0690	.0132	.19								
		.270	1.86	.1088	.0224	.21								
		.388	2.68	.1575	.0318	.20								
		.474	3.27	.2005	.0382	.19								
650	616	.126	.869	.0188	.0005	.03	6.7	46	150	1.03	[a].456	3.14	20	570
		.188	1.30	.0336	.0009	.03								
		.266	1.83	.0712	.0036	.05								
		.350	2.41	.1090	.0059	.05								
		.404	2.79	.1320	.0108	.06								
		.400	2.76	.1750	.0136	.08								
		.456	3.14	.2060	.0173	.08								
650	616	.150	1.03	.0247	.0016	.07	6.5	45	210	1.45	[a].520	3.59	20	450
		.232	1.60	.0435	.0031	.07								
		.300	2.07	.0710	.0052	.07								
		.410	2.83	.1340	.0147	.11								
		.520	3.59	.2001	.0260	.13								
750	672	.0204	.141	.0044	[b]-.0005	[c]-.12	4.3	30	31	.21	[a].0326	.225	20	540
		.0407	.281	.0127	-.0010	-.08								
		.0526	.363	.0315	-.0019	-.06								
		.0586	.404	.0705	-.0060	-.09								
		.0430	.296	.1205	-.0118	-.10								
		.0388	.268	.1615	-.0147	-.09								
		.0326	.225	.2000	-.0200	-.10								
[d]750	672	.0510	.352	.0112	[e]0	0	4.8	33	90	.62	.181	1.25	14.3	300
		.0842	.581	.0197	0	0								
		.122	.841	.0400	0	0								
		.158	1.09	.0840	0	0								
		.181	1.25	.1425	.0004	0								
750	672	.0169	.117	.0108	0	0	1.6	11	22	.15	[a].051	.35	20	450
		.0245	.169	.0223	0	0								
		.0291	.201	.0406	0	0								
		.0321	.221	.0882	0	0								
		.0392	.270	.1315	0	0								
		.0460	.317	.1735	0	0								
		.0510	.352	.2000	0	0								

[a]Stress at 20% strain.
[b]Post examination of specimen revealed slight indentation from scissors.
[c]Negative values due to negative values of lateral strain resulting from degradation phenomena.
[d]Specimen overheated to 775° F (686° K), cooled to 750° F (672° K), and tested to 14.3% strain.
[e]Scissor force reduced.

TABLE 12.- COMPRESSIVE PROPERTIES OF FILLED SILICONE RESIN (SRI)

Temperature		Stress		Axial strain	Lateral strain	Poisson's ratio	Young's modulus		Yield strength at 0.2% offset		Ultimate strength		Total compression, %	Load time to rupture, s
°F	°K	ksi	MN/m²				ksi	MN/m²	psi	MN/m²	ksi	MN/m²		
-200	144	0.348	2.40	0.0040	0.0037	0.92	87	600	450	3.10	[a]1.485	10.24	21.3	270
		.615	4.24	.0127	.0105	.83								
		.872	6.01	.0336	.0266	.79								
		1.000	6.895	.0622	.0460	.74								
		1.065	7.343	.0910	.0705	.77								
		1.330	9.170	.1425	.0808	.56								
		1.485	10.24	.2130	.0950	.45								
-200	144	.256	1.77	.0265	.0002	0	9.9	68	250	1.72	[a].758	5.23	19.8	300
		.343	2.37	.0477	.0003	0								
		.512	3.53	.1025	.0004	0								
		.665	4.59	.1500	.0005	0								
		.758	5.23	.1980	.0006	0								
-200	144	.154	1.06	.0077	.0002	.03	20	140	300	2.07	[a].980	6.76	20.1	300
		.386	2.66	.0274	.0005	.02								
		.601	4.14	.0620	.0007	.01								
		.854	5.89	.1850	.0022	.01								
		.980	6.76	.2010	.0063	.03								
[b]-200	144	.568	3.92	.0065	.0005	.08	88	610	1120	7.722	[a]1.800	12.41	20.3	330
		1.100	7.584	.0147	.0006	.04								
		1.450	9.998	.0309	.0007	.02								
		1.560	10.76	.0692	.0052	.08								
		1.800	12.41	.2030	.0555	.27								
[c]-170	161	.143	.986	.0059	0	0	25	170	600	4.14	[a]1.290	8.895	20	300
		.415	2.86	.0150	.0001	0								
		.686	4.73	.0332	.0002	0								
		1.135	7.826	.0927	.0006	0								
		1.290	8.895	.2000	.0035	.02								
-100	200	.082	.56	.0122	.0042	.34	6.6	46	140	.965	[a].500	3.45	21.5	480
		.182	1.25	.0344	.0115	.33								
		.300	2.07	.0745	.0250	.34								
		.382	2.63	.1220	.0425	.35								
		.500	3.45	.2150	.0955	.44								
-100	200	.172	1.19	.0138	0	0	12.6	86.9	235	1.62	.740	5.10	27	360
		.241	1.66	.0217	0	0								
		.342	2.36	.0422	.0006	.02								
		.422	2.91	.0666	.0011	.02								
		.568	3.92	.1130	.0072	.06								
		.768	5.29	.2160	.0686	.32								
		.863	5.95	.2700	.0800	.32								
-100	200	.115	.793	.0089	.0061	.68	13.5	93.1	180	1.24	[a].550	3.79	20.7	330
		.200	1.38	.0189	.0140	.74								
		.285	1.96	.0370	.0224	.60								
		.345	2.38	.0555	.0305	.55								
		.425	2.93	.0955	.0467	.49								
		.505	3.48	.1550	.0705	.46								
		.550	3.79	.2070	.0825	.40								
-100	200	.0718	.495	.0235	.0111	.47	2.9	20	180	1.24	[a].333	2.30	19.5	300
		.154	1.06	.0518	.0240	.47								
		.225	1.55	.1001	.0443	.44								
		.307	2.12	.1505	.0610	.41								
		.333	2.30	.1950	.0930	.48								
[c]-100	200	.060	.41	.0103	.0005	.05	5.8	40	110	.758	[a].395	2.72	20.5	330
		.153	1.05	.0317	.0051	.16								
		.265	1.83	.0800	.0148	.19								
		.321	2.21	.1220	.0280	.23								
		.395	2.72	.2050	.0465	.23								
0	255	.085	.59	.0355	.0111	.31	2.3	16	140	.965	[a].273	1.88	20.2	360
		.155	1.07	.0712	.0249	.35								
		.212	1.46	.1140	.0419	.37								
		.244	1.68	.1510	.0550	.36								
		.273	1.88	.2020	.0797	.39								
0	255	.077	.53	.0344	.0092	.27	2.2	15	98	.68	[a].266	1.83	20	330
		.136	.937	.0656	.0236	.36								
		.196	1.35	.1078	.0385	.36								
		.237	1.63	.1498	.0583	.39								
		.266	1.83	.2000	.0790	.40								
70	294	.074	.51	.0378	.0071	.19	2.0	14	120	.827	[a].230	1.59	21.1	390
		.115	.792	.0595	.0160	.27								
		.160	1.10	.0918	.0242	.26								
		.204	1.41	.1520	.0327	.22								
		.230	1.59	.2110	.0384	.18								
70	294	.080	.55	.0311	.0136	.44	2.6	18	110	.758	[a].260	1.79	20.4	360
		.130	.896	.0578	.0232	.40								
		.195	1.34	.1042	.0399	.38								
		.238	1.64	.1585	.0582	.37								
		.260	1.79	.2040	.0780	.38								

[a]Stress at 20% strain.

[b]Specimen cooled to -300° F (89° K), warmed up to -200° F (145° K), and soaked at -200° F (145° K) for 30 minutes (1800 seconds).

[c]Soaked at temperature for 30 minutes (1800 seconds).

TABLE 12.- COMPRESSIVE PROPERTIES OF FILLED SILICONE RESIN (SRI) - Concluded

Temperature		Stress		Axial strain	Lateral strain	Poisson's ratio	Young's modulus		Yield strength at 0.2% offset		Ultimate strength		Total compression, %	Load time to rupture, s
°F	°K	ksi	MN/m²				ksi	MN/m²	psi	MN/m²	ksi	MN/m²		
150	339	0.058	0.40	0.0270	0.0114	0.43	2.0	14	115	.793	[a].226	1.56	19.4	300
		.118	.814	.0624	.0253	.41								
		.168	1.16	.0995	.0397	.40								
		.200	1.38	.1380	.0546	.40								
		.226	1.56	.1935	.0732	.38								
150	339	.093	.64	.0430	.0162	.38	2.1	14	115	.793	[a].239	1.65	19.7	270
		.151	1.04	.0769	.0298	.39								
		.190	1.31	.1070	.0410	.38								
		.212	1.46	.1450	.0585	.40								
		.239	1.65	.1970	.0719	.37								
250	394	.0795	.548	.0412	.0145	.35	1.9	13	108	.745	[a].212	1.46	19.8	240
		.115	.793	.0662	.0235	.36								
		.152	1.05	.0989	.0346	.35								
		.193	1.33	.1560	.0558	.36								
		.212	1.46	.1980	.0707	.36								
250	394	.0835	.576	.0512	.0157	.31	1.6	11	100	.690	[a].202	1.39	20	210
		.117	.807	.0750	.0235	.31								
		.144	.993	.1005	.0311	.31								
		.175	1.21	.1495	.0467	.31								
		.202	1.39	.2002	.0672	.33								
350	450	.0825	.569	.0441	.0168	.38	1.9	13	145	1.00	[a].248	1.71	20	150
		.135	.931	.0705	.0300	.43								
		.183	1.26	.1062	.0488	.46								
		.214	1.48	.1480	.0681	.46								
		.248	1.71	.1998	.0922	.46								
350	450	.0804	.554	.0318	.0138	.43	2.3	16	120	.827	[a].246	1.70	19.9	150
		.115	.793	.0485	.0192	.40								
		.118	.814	.0912	.0378	.42								
		.215	1.48	.1370	.0567	.41								
		.246	1.70	.1985	.0822	.41								
350	450	.090	.62	.0456	.0047	.10	2.0	14	110	.758	[a].240	1.65	20	420
		.148	1.02	.0758	.0180	.24								
		.180	1.24	.1095	.0377	.34								
		.238	1.64	.1618	.0687	.42								
		.240	1.66	.2000	.0874	.44								
450	505	.0638	.440	.0471	.0178	.38	1.3	9.0	124	.855	.177	1.22	20.4	270
		.104	.717	.0794	.0332	.42								
		.152	1.05	.1235	.0676	.55								
		.188	1.30	.1760	.0860	.49								
		.177	1.22	.2042	.0937	.46								
450	505	.0714	.492	.0371	.0169	.46	2.0	14	95	.65	.210	1.45	18.8	300
		.123	.848	.0706	.0375	.53								
		.160	1.10	.1043	.0565	.54								
		.184	1.27	.1315	.0682	.52								
		.210	1.45	.1883	.0942	.50								
550	561	.0745	.514	.0648	.0148	.23	1.2	8.3	130	.896	.186	1.28	21.5	180
		.118	.814	.1015	.0292	.29								
		.156	1.08	.1395	.0486	.35								
		.176	1.21	.1780	.0660	.37								
		.186	1.28	.2150	.0808	.38								
550	561	.0586	.404	.0421	.0099	.24	1.4	9.6	235	1.62	.235	1.62	16.7	150
		.0908	.626	.0662	.0199	.30								
		.135	.931	.1005	.0339	.34								
		.174	1.20	.1390	.0492	.35								
		.235	1.62	.1665	.0694	.42								
650	616	.0397	.274	.0424	.0080	.19	.97	6.7	72	.49	.108	.745	16.5	150
		.0627	.432	.0700	.0154	.22								
		.0856	.590	.1005	.0252	.25								
		.102	.703	.1305	.0329	.25								
		.108	.745	.1650	.0381	.23								
650	616	.0387	.267	.0041	.0066	.16	.94	6.5	60	.41	.100	.690	16	150
		.0618	.426	.0659	.0151	.23								
		.0817	.563	.0977	.0243	.25								
		.0962	.663	.1285	.0318	.25								
		.100	.690	.1595	.0412	.26								
750	672	.0147	.101	.0294	0	0	.50	3.4	17	.12	[a].034	.23	20	270
		.0218	.150	.0591	0	0								
		.0284	.196	.1032	0	0								
		.0305	.210	.1495	.0001	0								
		.0340	.234	.2000	.0002	0								
750	672	.0116	.800	.0247	-.0008	[d]-.03	.48	3.3	15	.10	[a].0316	.218	20	240
		.0186	.128	.0570	-.0016	-.03								
		.0266	.183	.1018	-.0022	-.02								
		.0293	.202	.1463	-.0036	-.02								
		.0316	.218	.2000	-.0039	-.02								

[a]Stress at 20% strain.

[d]Negative values due to negative values of lateral strain resulting from degradation phenomena.

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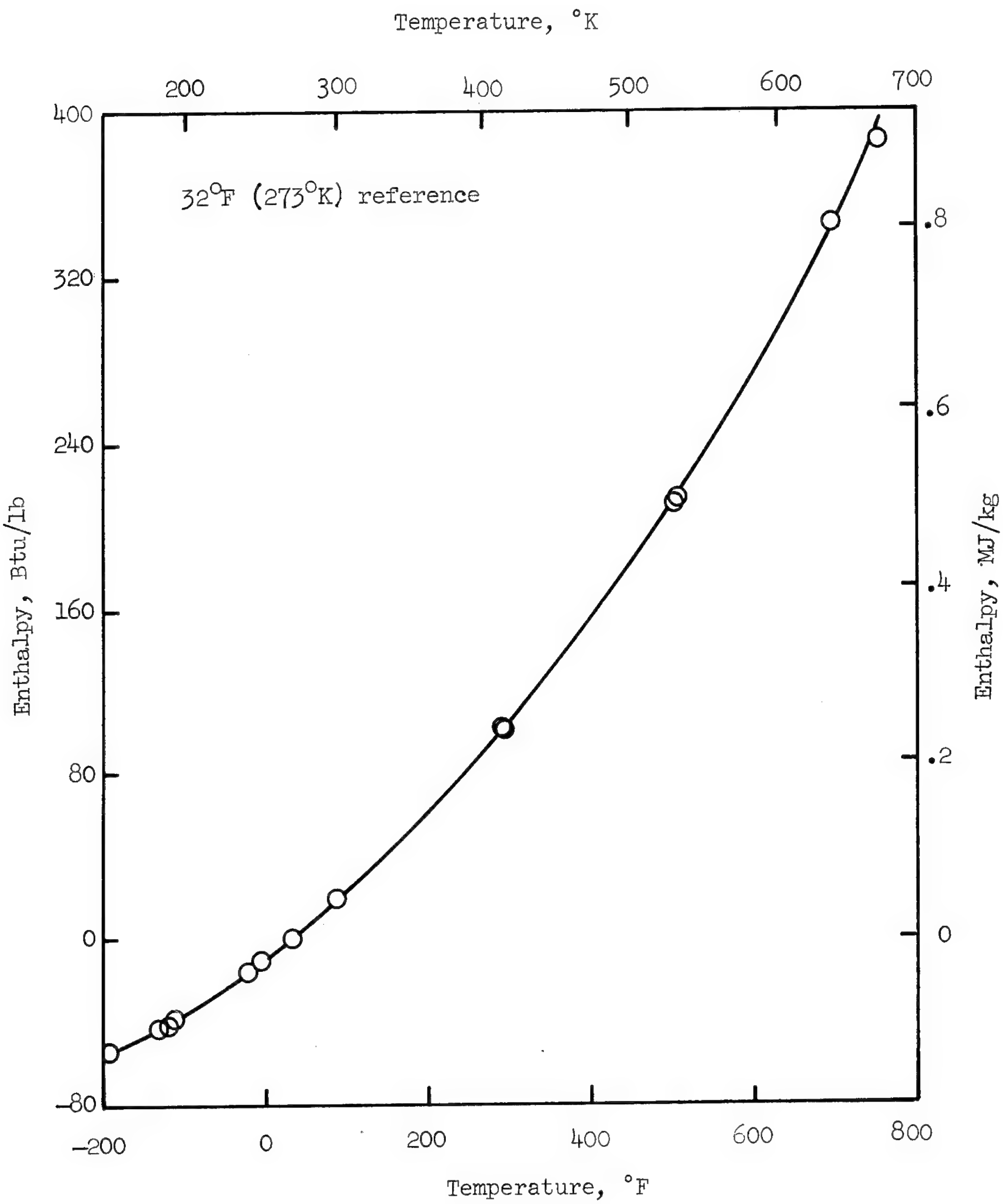


Figure 1.- Enthalpy of high-density phenolic-nylon (Melpar).

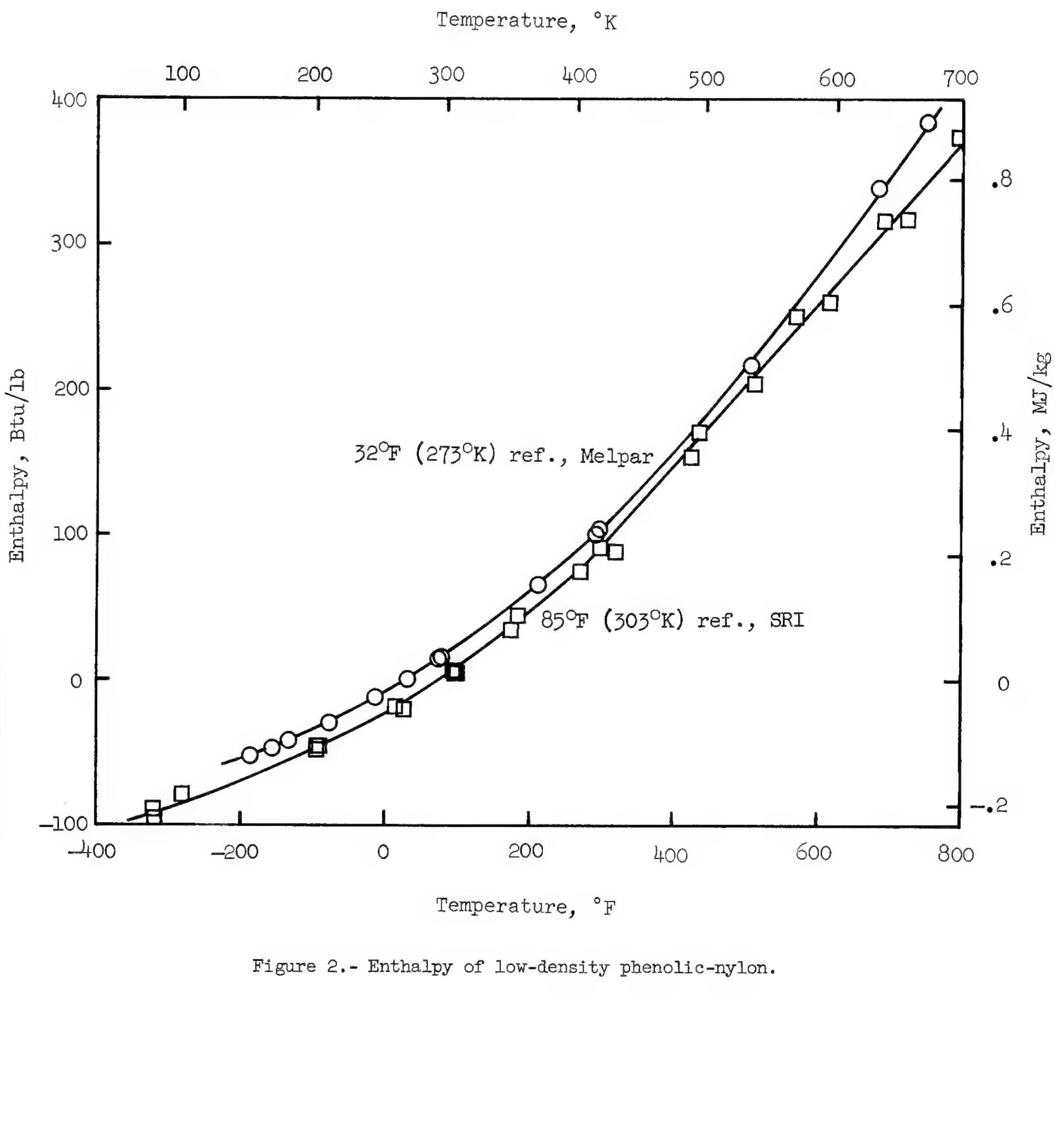


Figure 2.- Enthalpy of low-density phenolic-nylon.

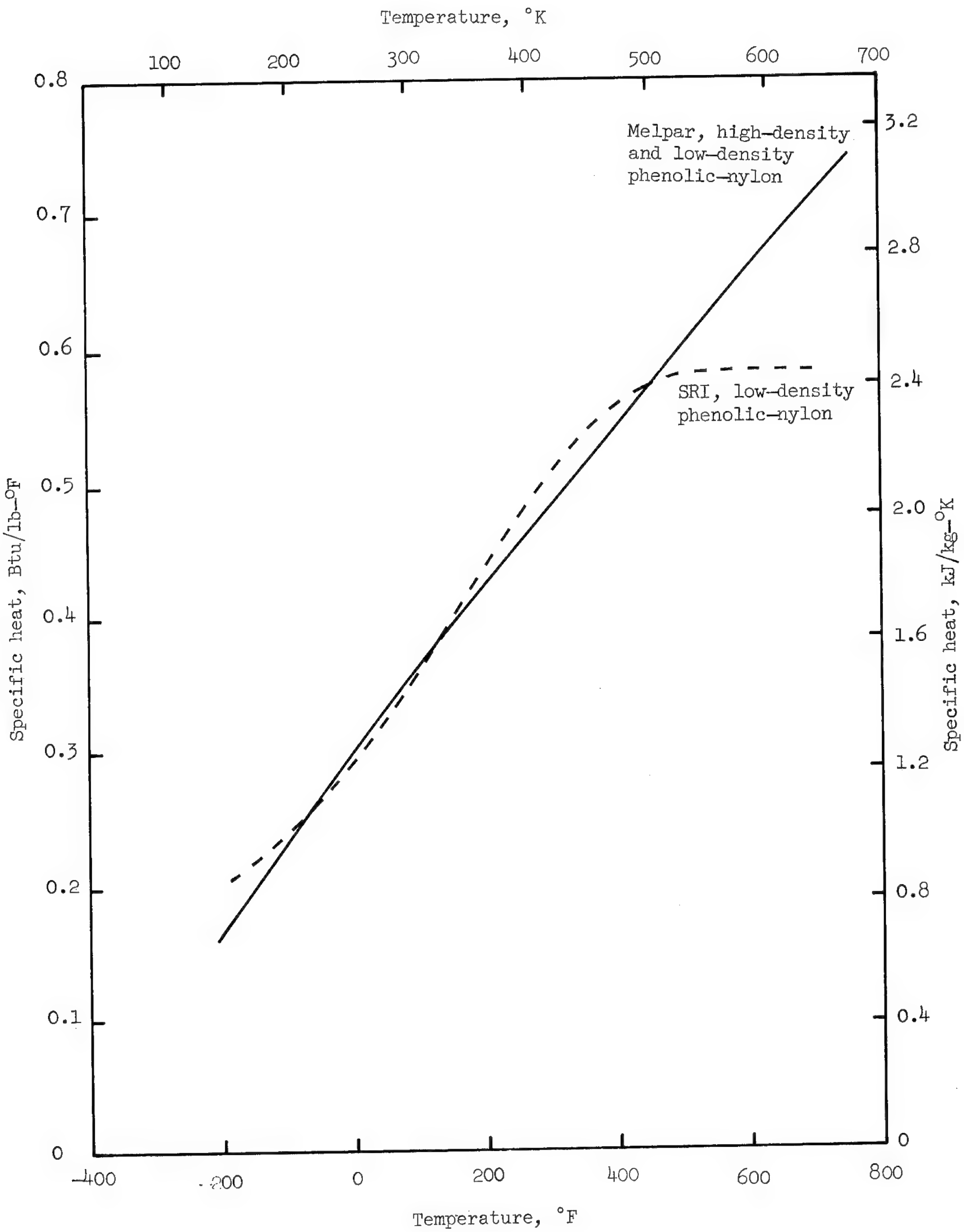


Figure 3.- Specific heat of phenolic-nylon calculated from figures 1 and 2.

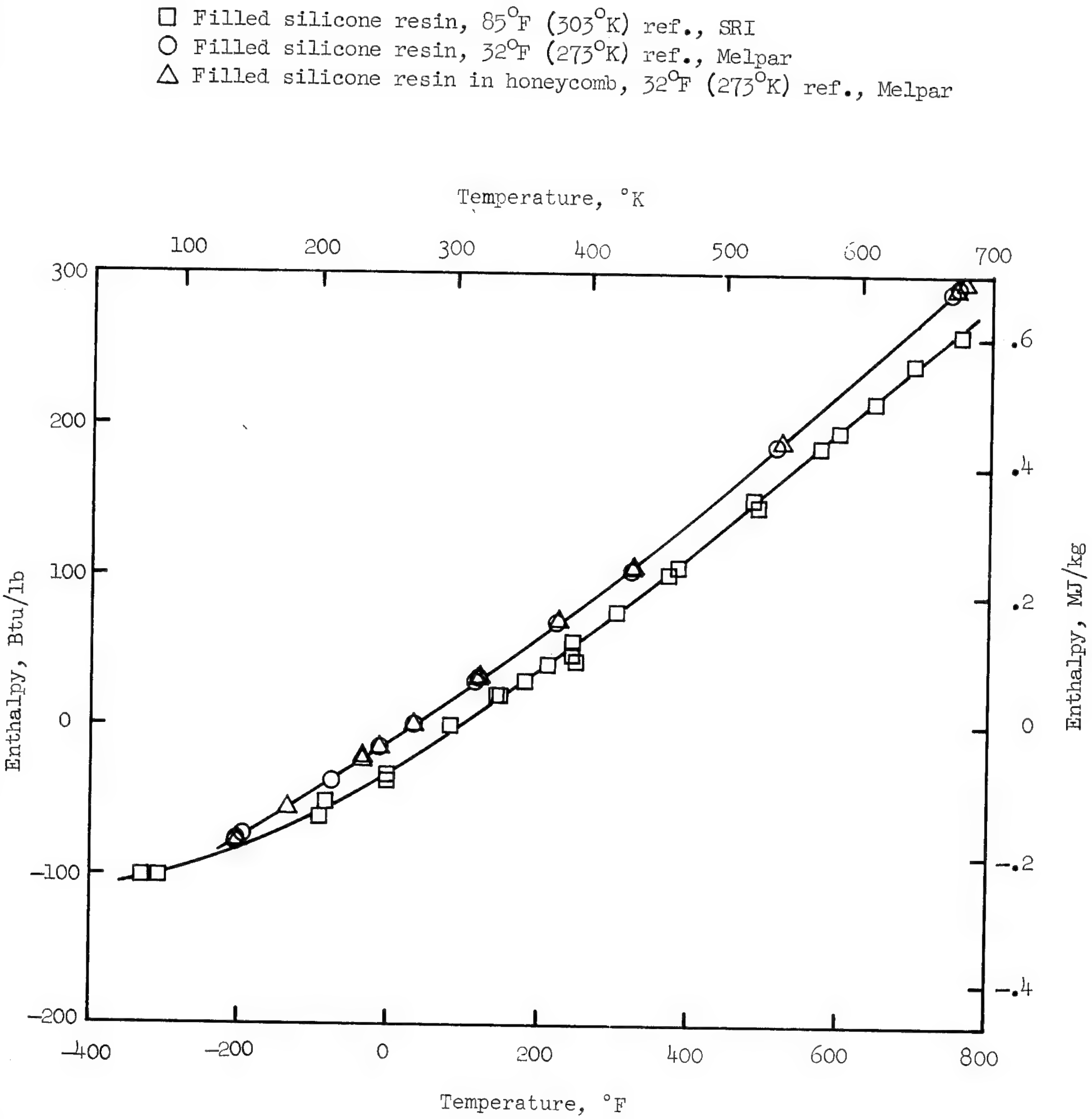


Figure 4.- Enthalpy of filled silicone resin.

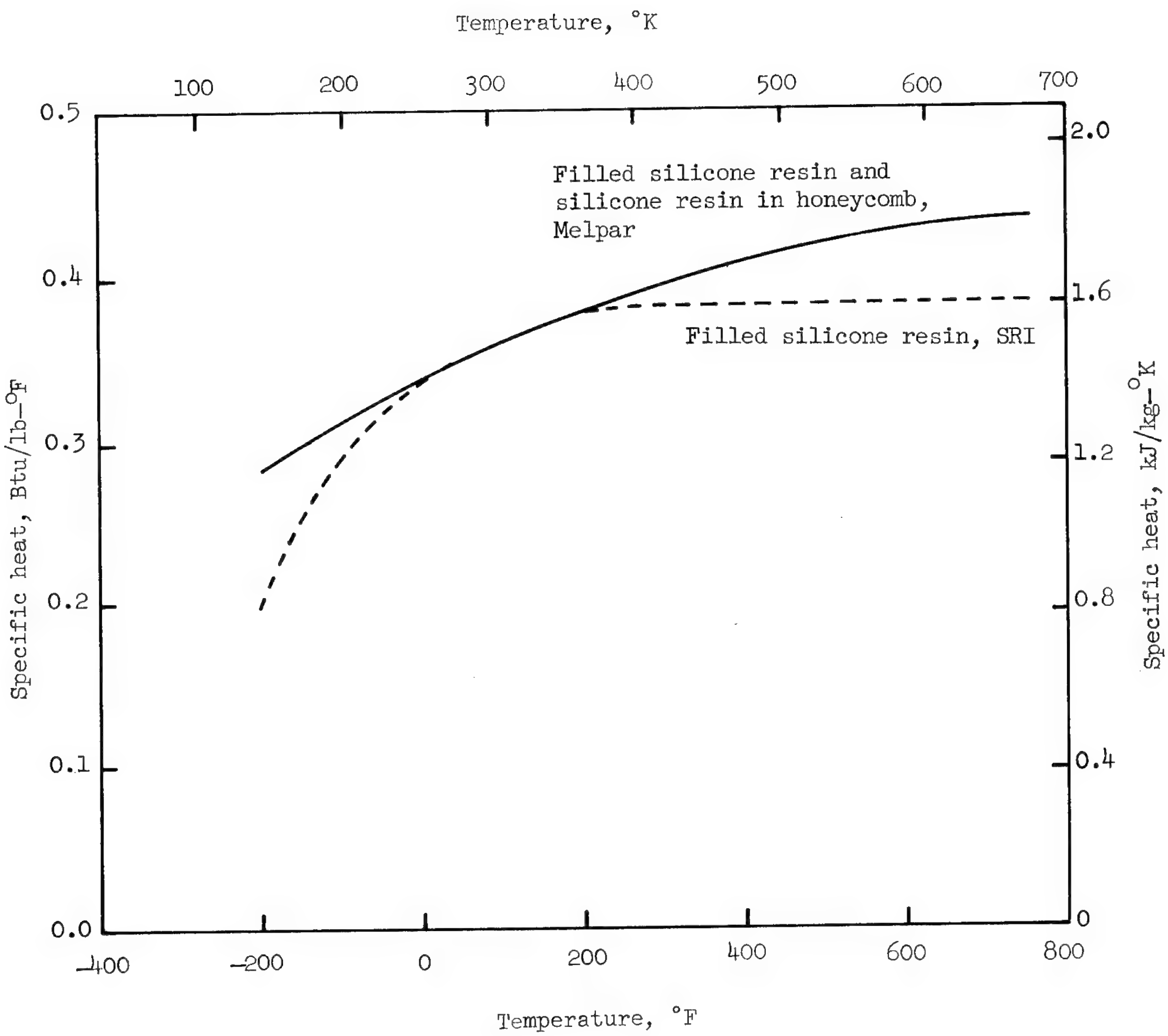


Figure 5.- Specific heat of filled silicone resin calculated from figure 4.

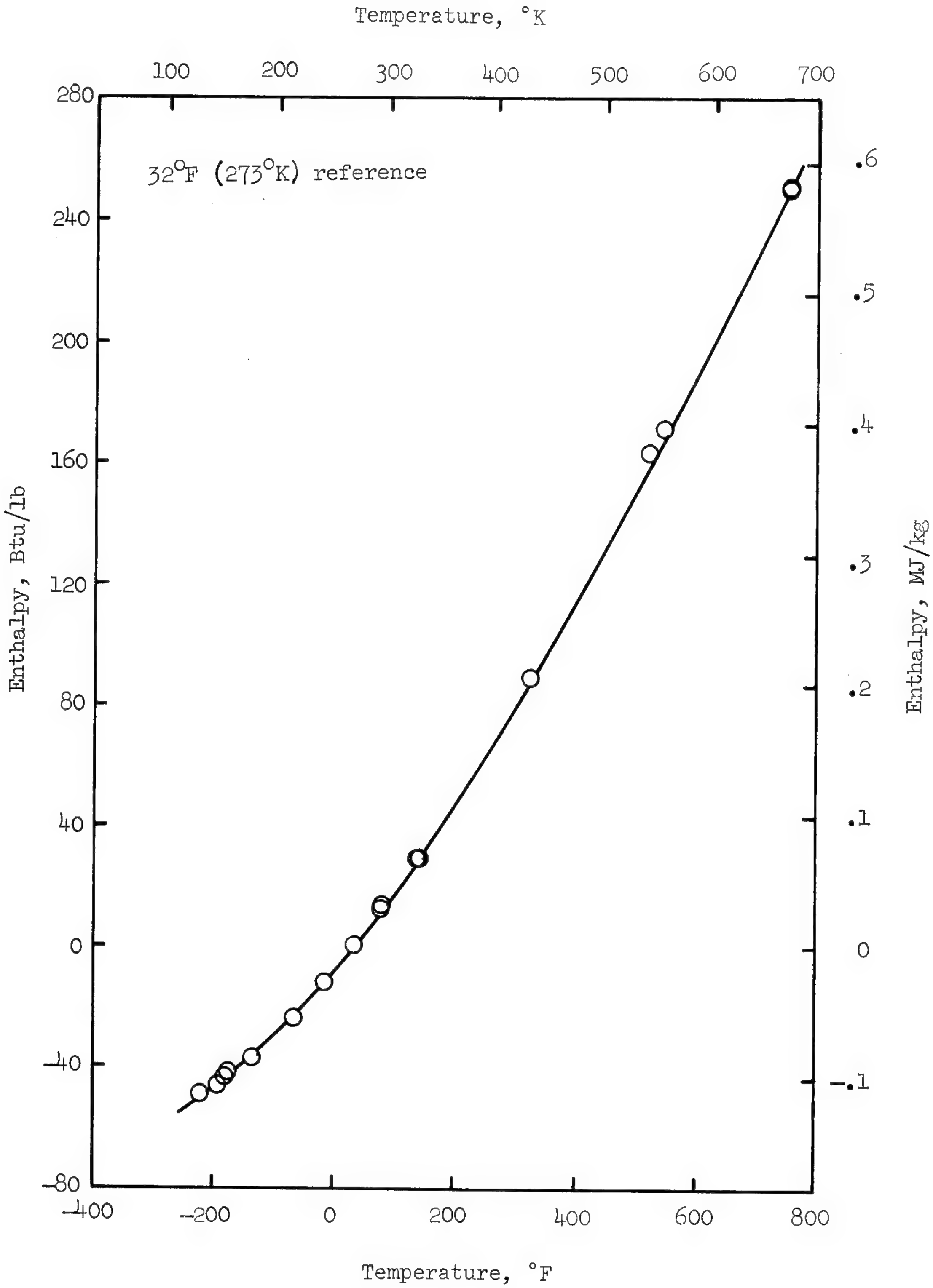


Figure 6.- Enthalpy of Narmco 4028 carbon-fiber-reinforced phenolic (Melpar).

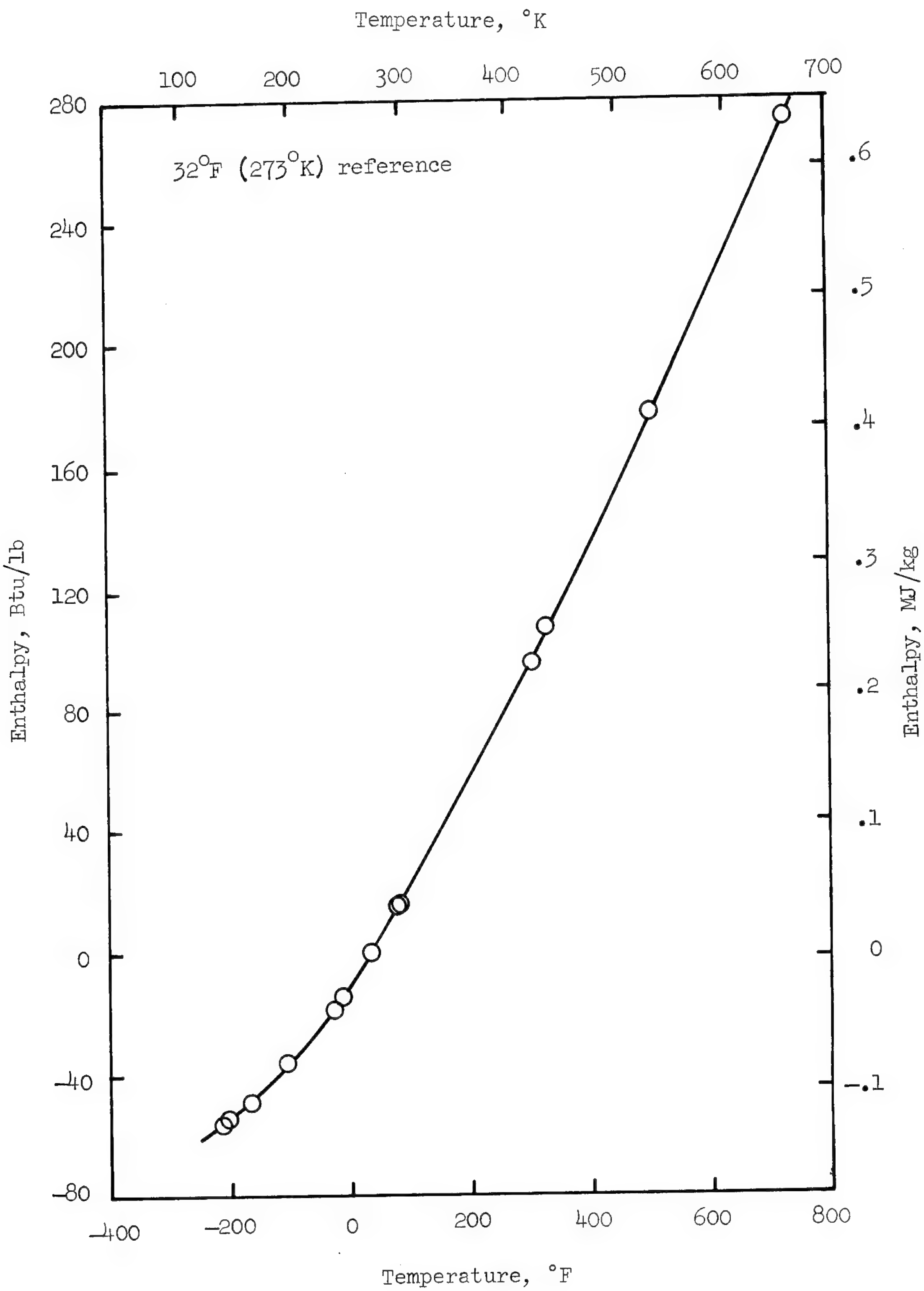


Figure 7.- Enthalpy of Avcoat 5026-39-HC G filled epoxy in honeycomb (Melpar).

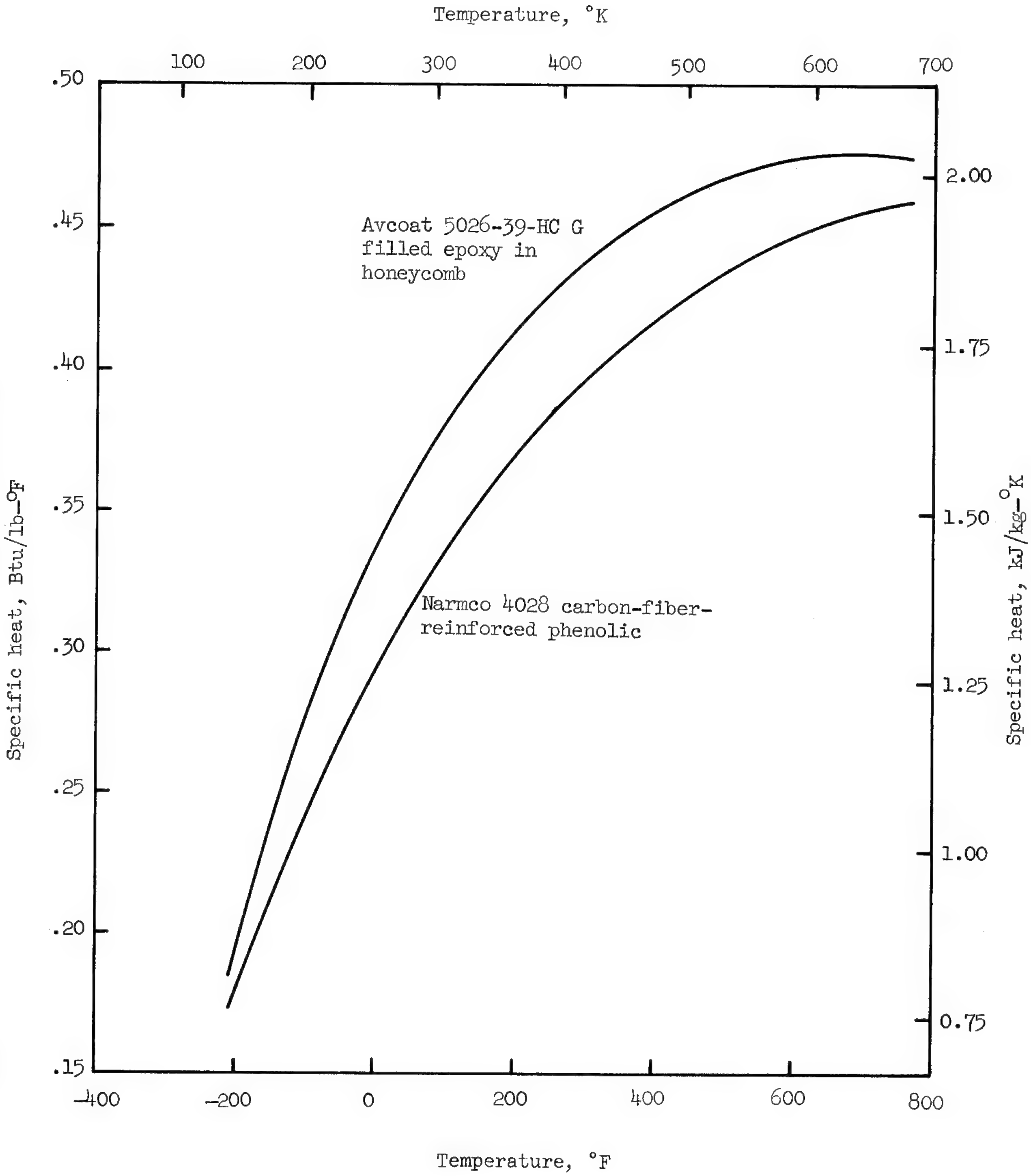


Figure 8.- Specific heat of Narmco 4028 carbon-fiber-reinforced phenolic and Avcoat 5026-39-HC G filled epoxy in honeycomb calculated from figures 6 and 7 (Melpar).

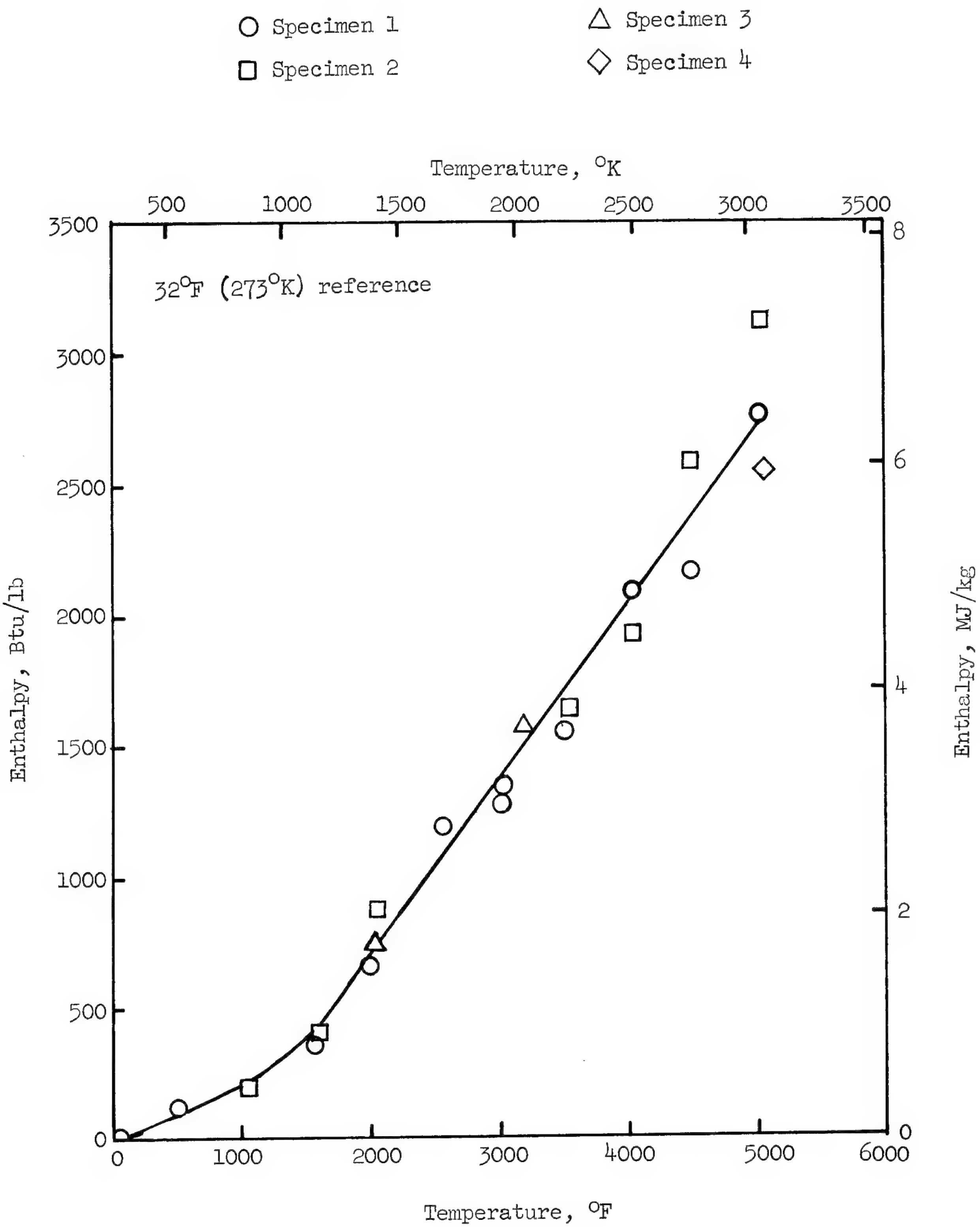


Figure 9.- Enthalpy of high-density phenolic-nylon char (SRI).

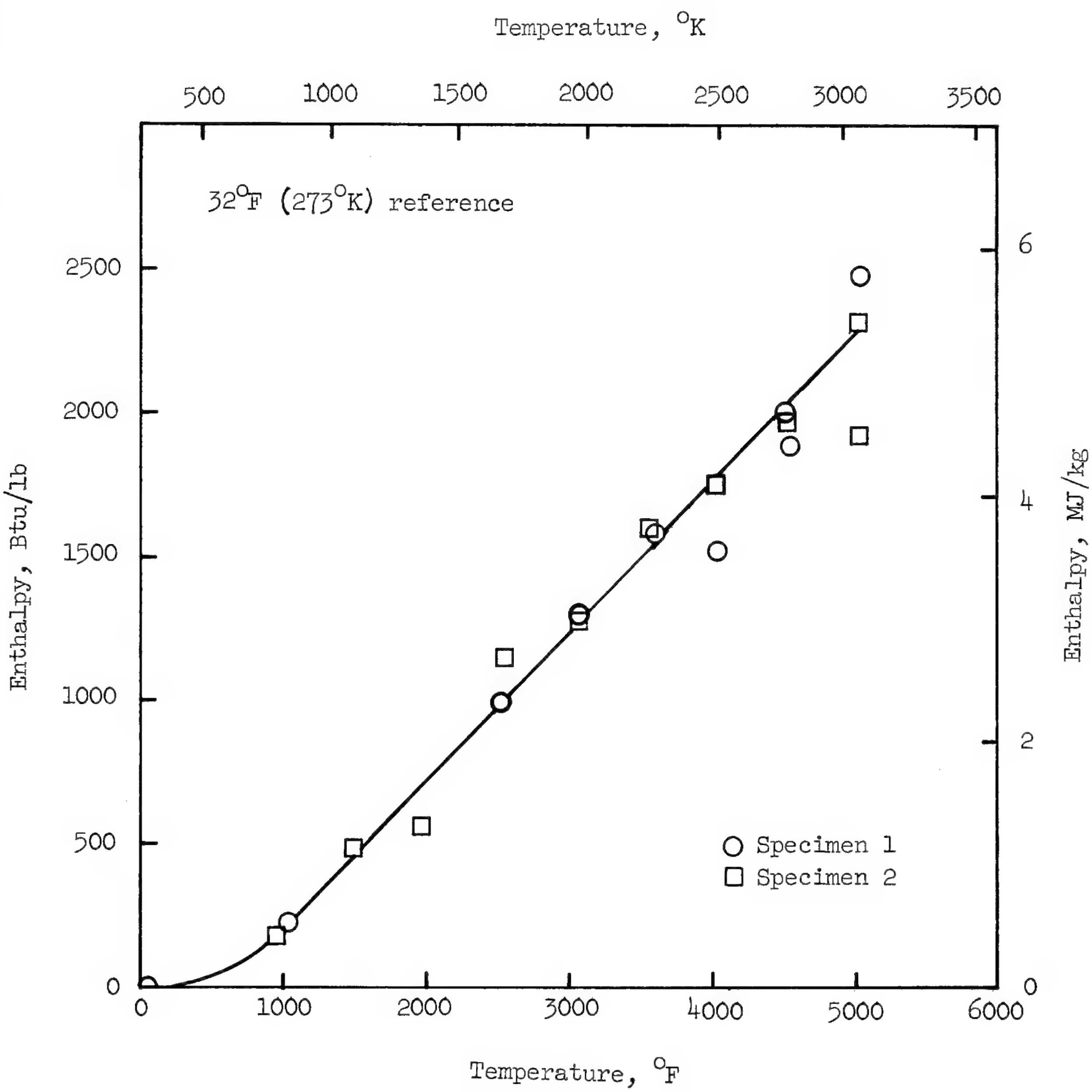


Figure 10.- Enthalpy of low-density phenolic-nylon char (SRI).

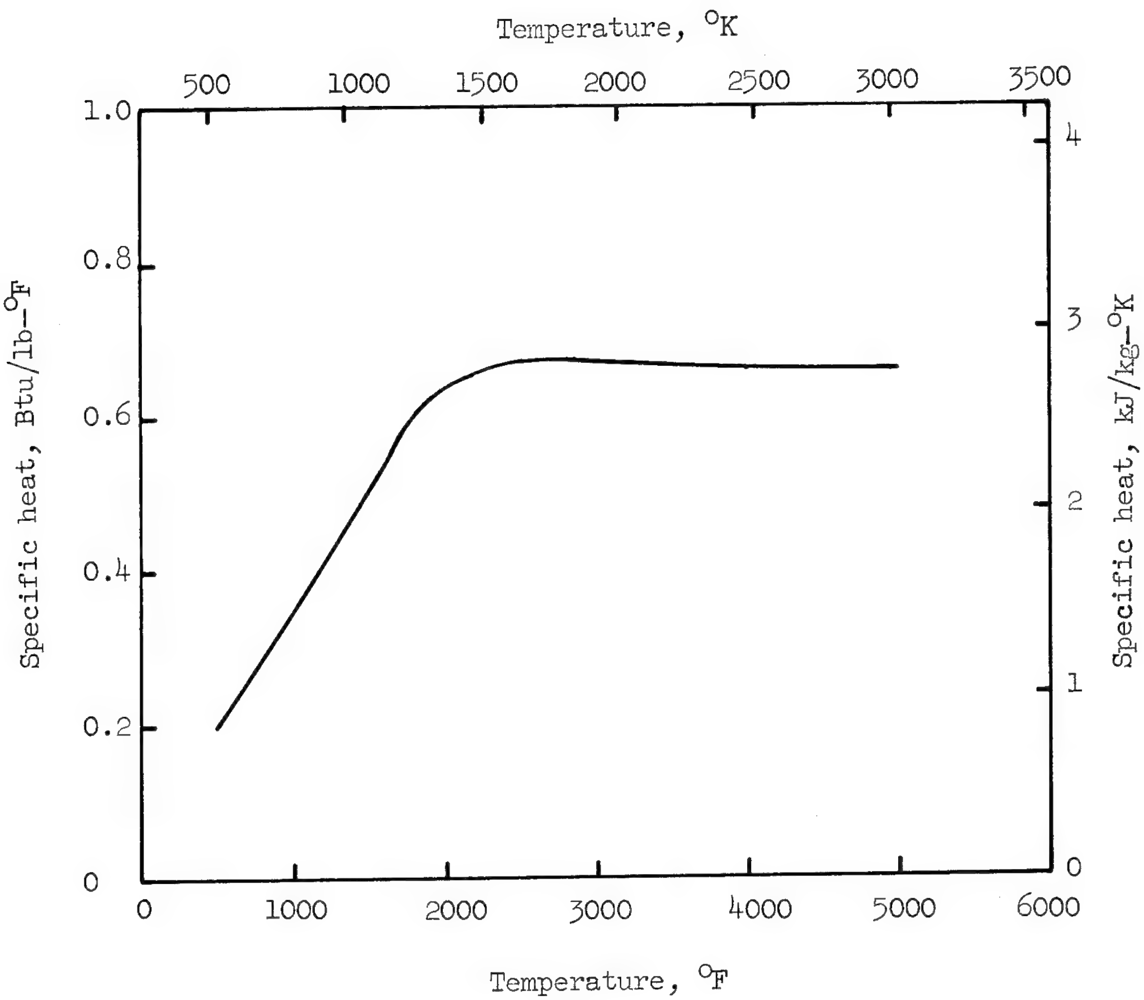


Figure 11.- Specific heat of high-density phenolic-nylon char, calculated from figure 9 (SRI).

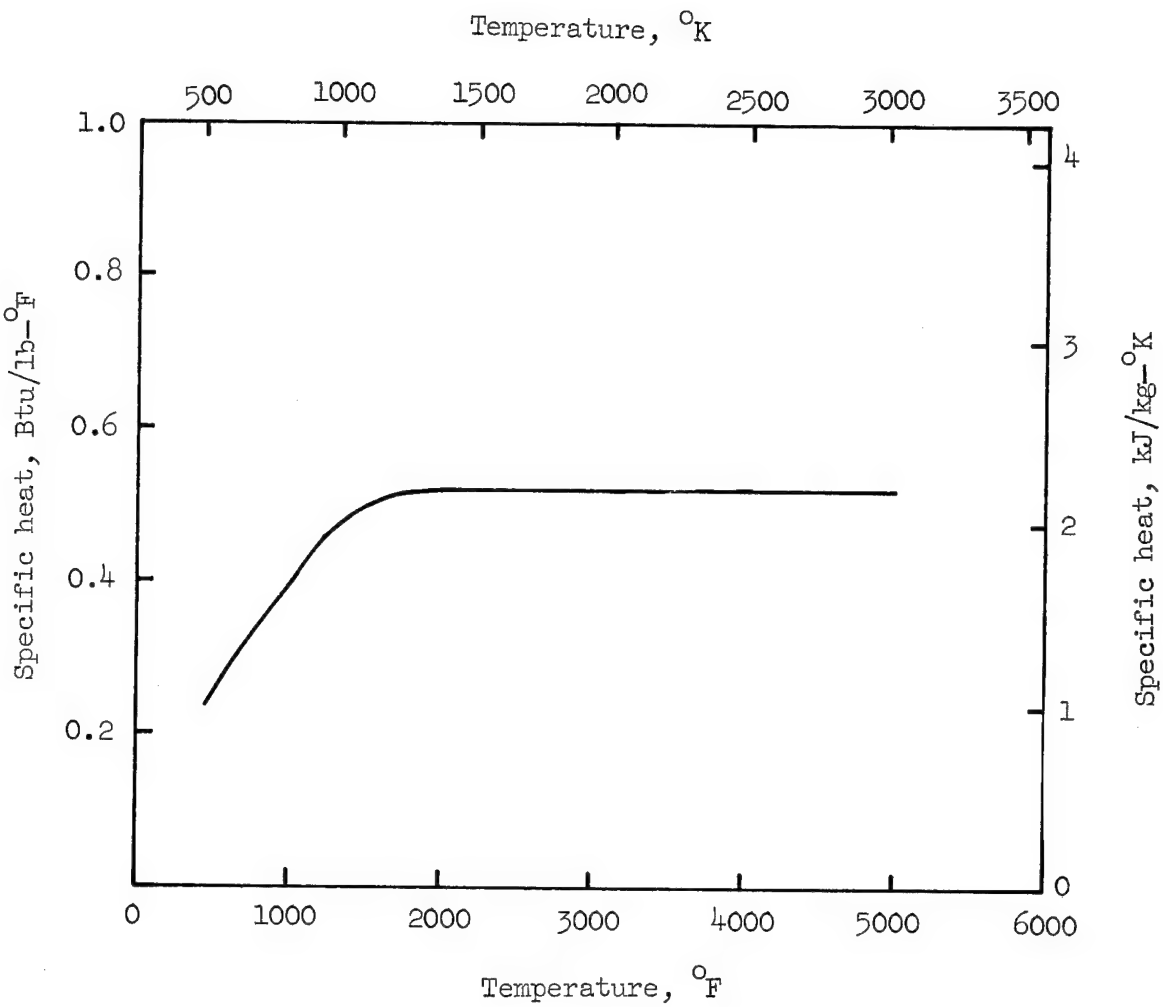


Figure 12.- Specific heat of low-density phenolic-nylon char, calculated from figure 10 (SRI).

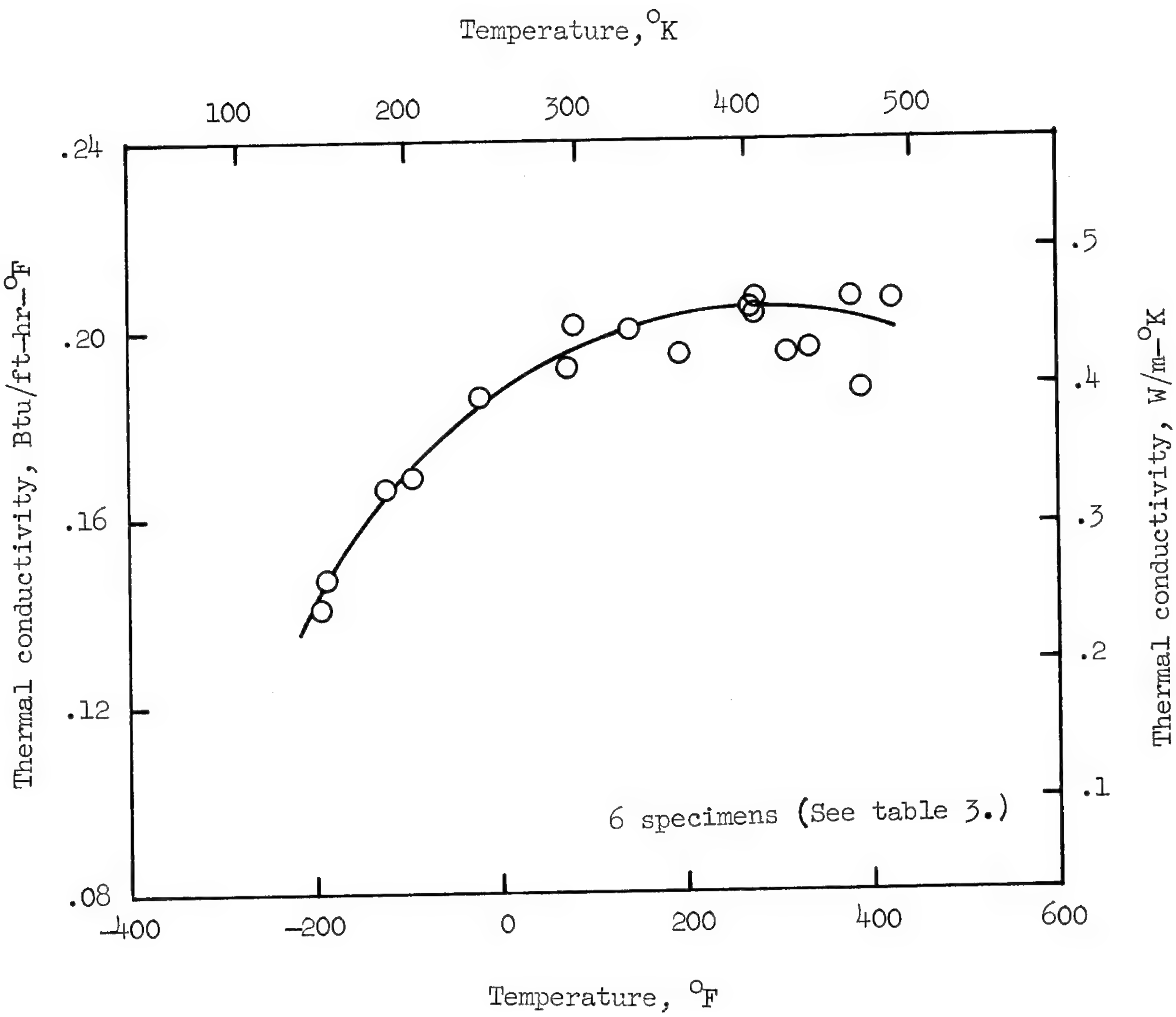
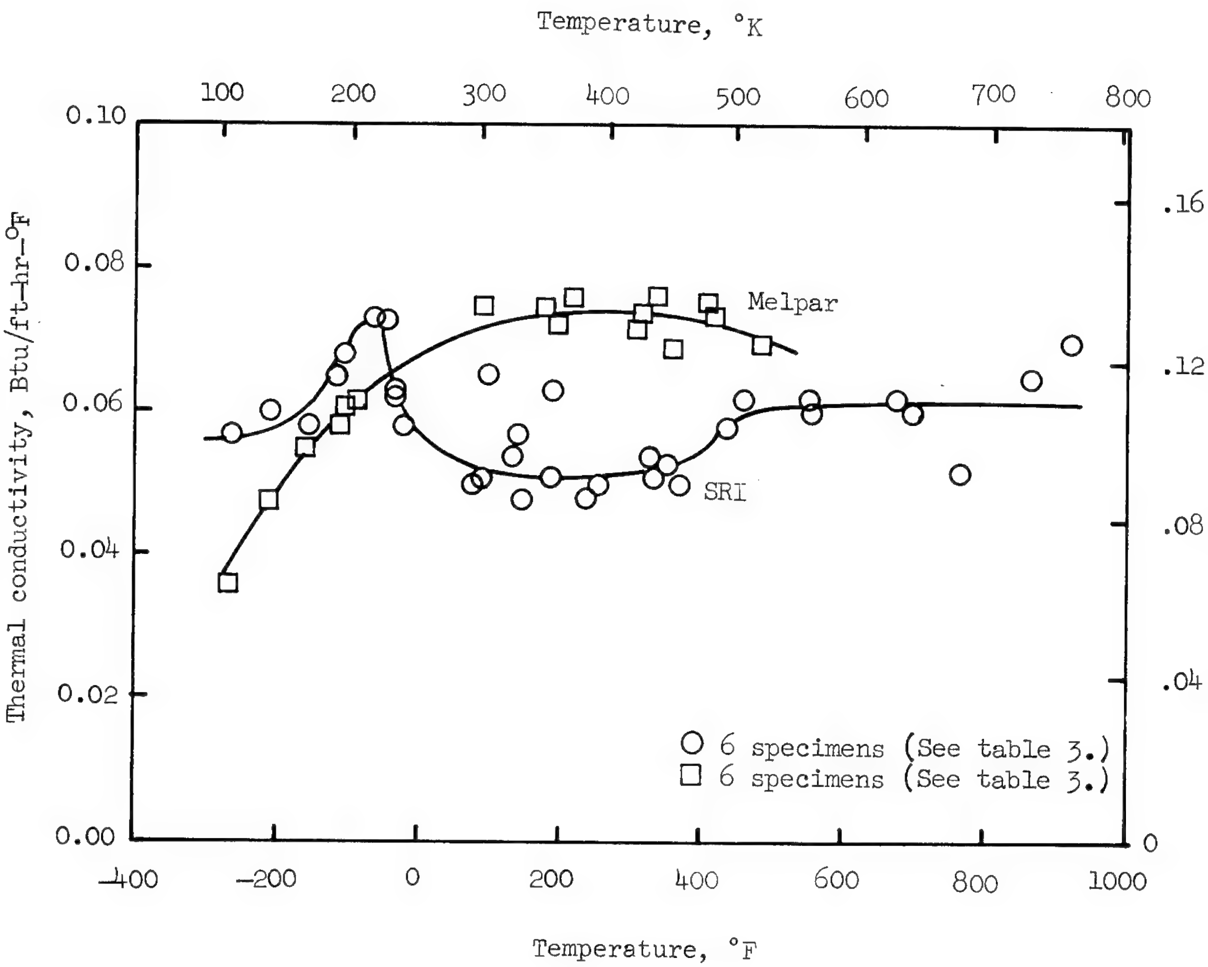


Figure 13.- Thermal conductivity of high-density phenolic-nylon (Melpar).



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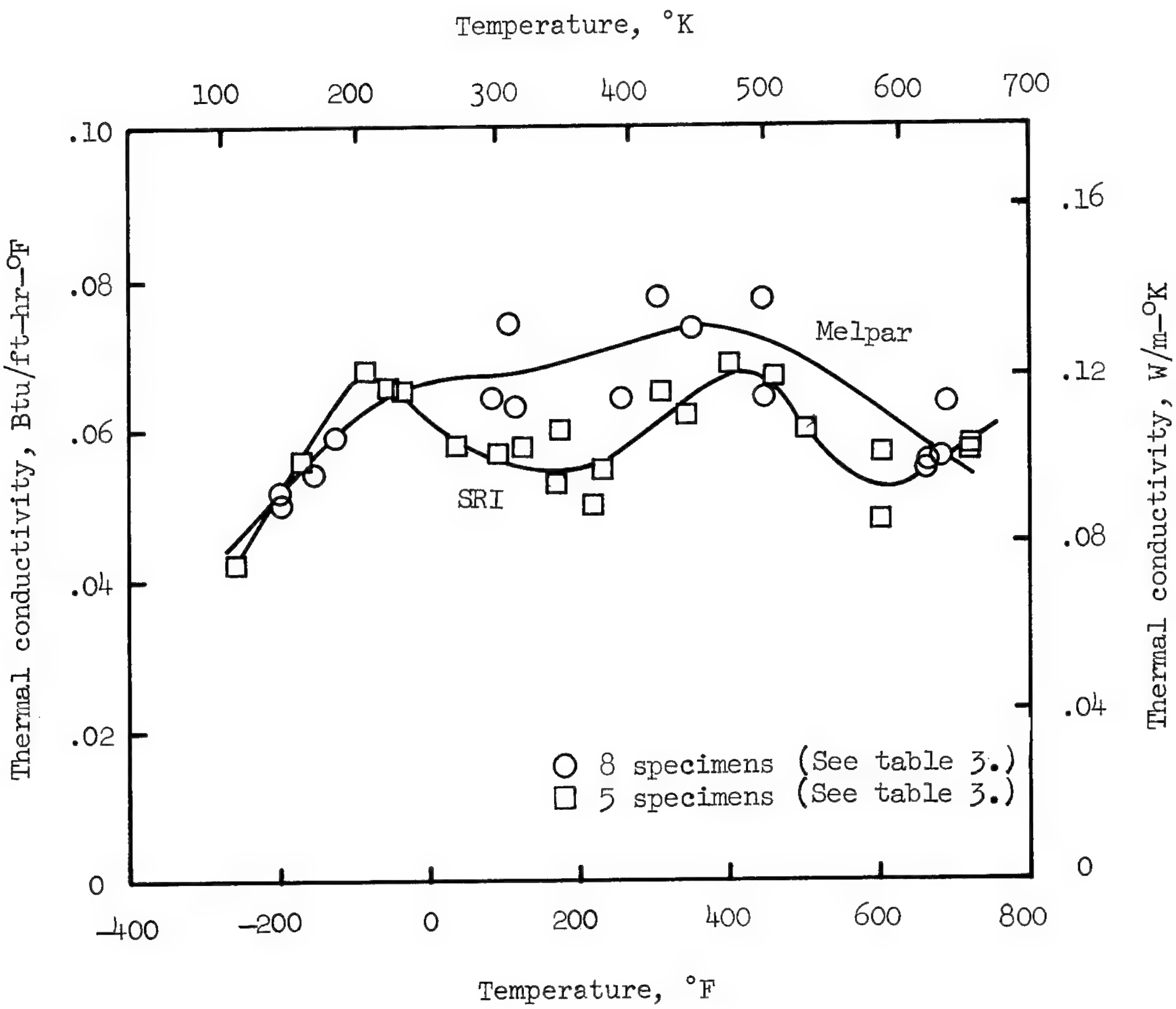


Figure 15.- Thermal conductivity of filled silicone resin.

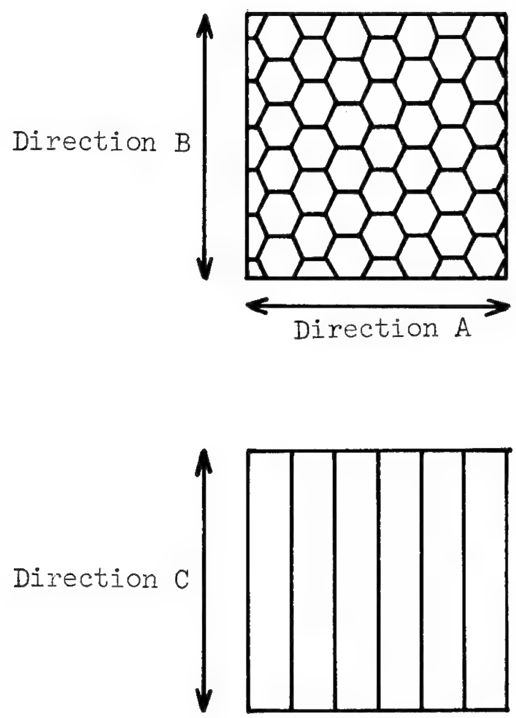


Figure 16.- Direction designation for honeycomb materials.

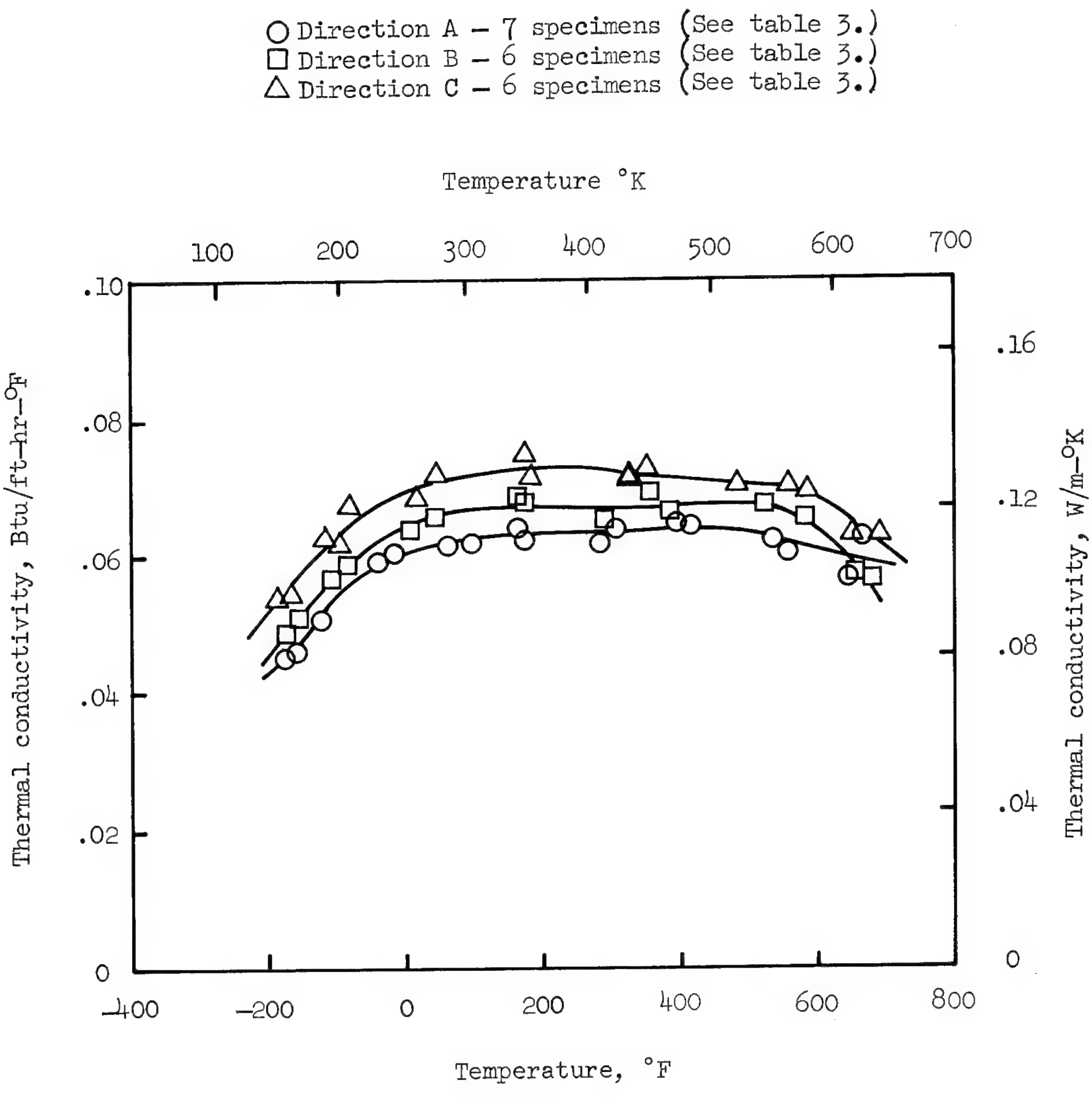


Figure 17.- Thermal conductivity of filled silicone resin in honeycomb plotted against temperature (Melpar).

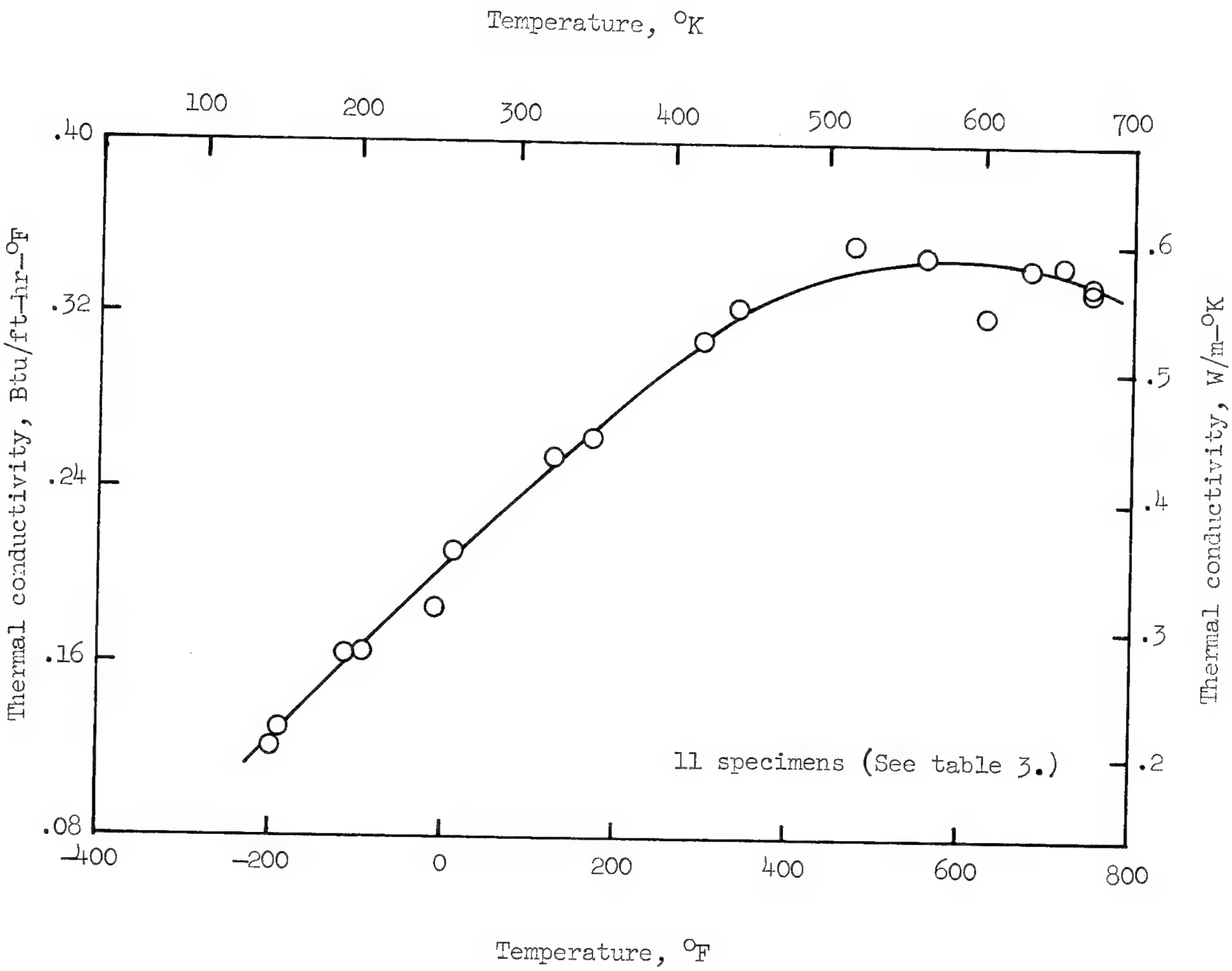


Figure 18.- Thermal conductivity of Narmco 4028 carbon-fiber-reinforced phenolic (Melpar).

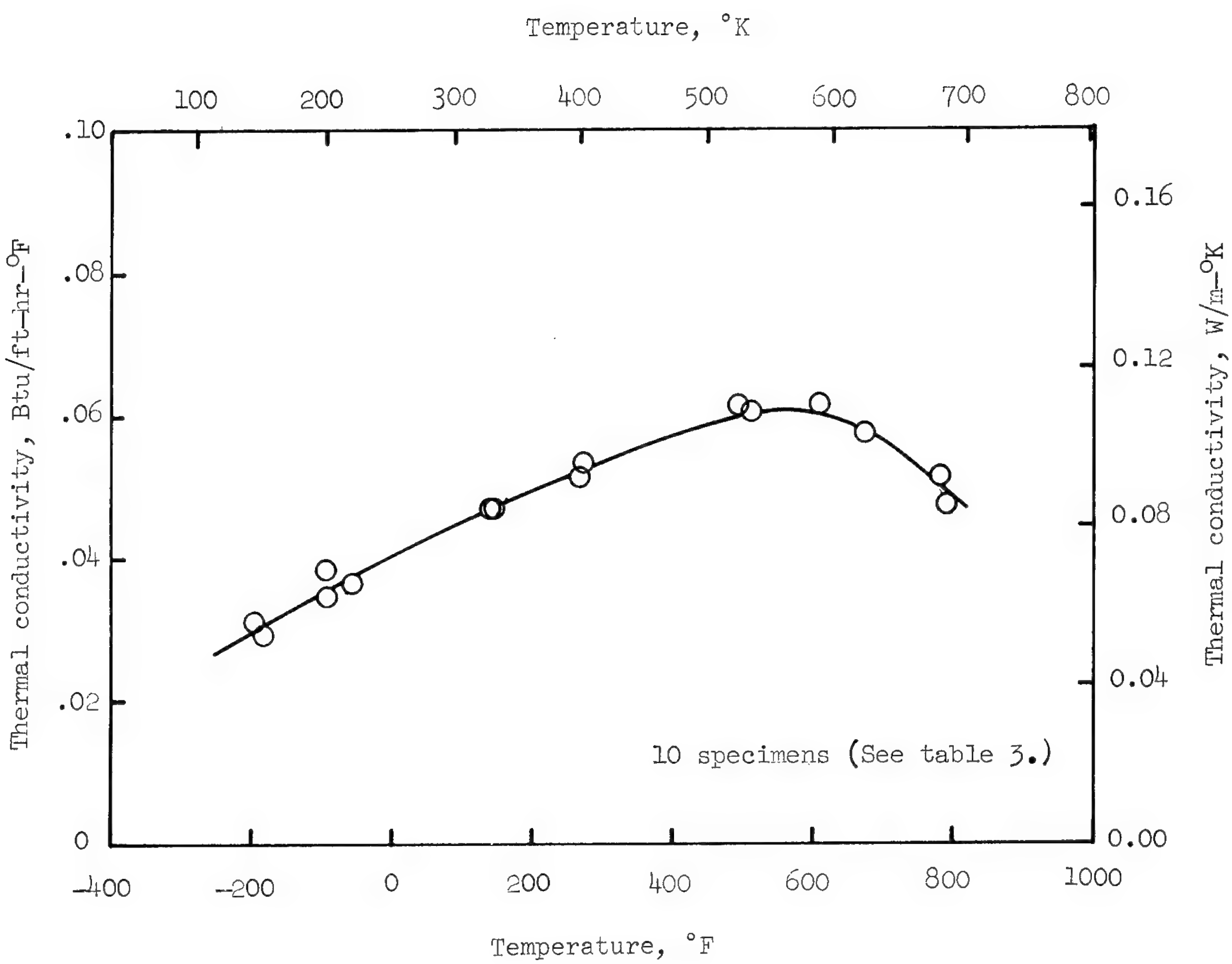


Figure 19.- Thermal conductivity of Avcoat 5026-39-HC G filled epoxy in honeycomb (Melpar).

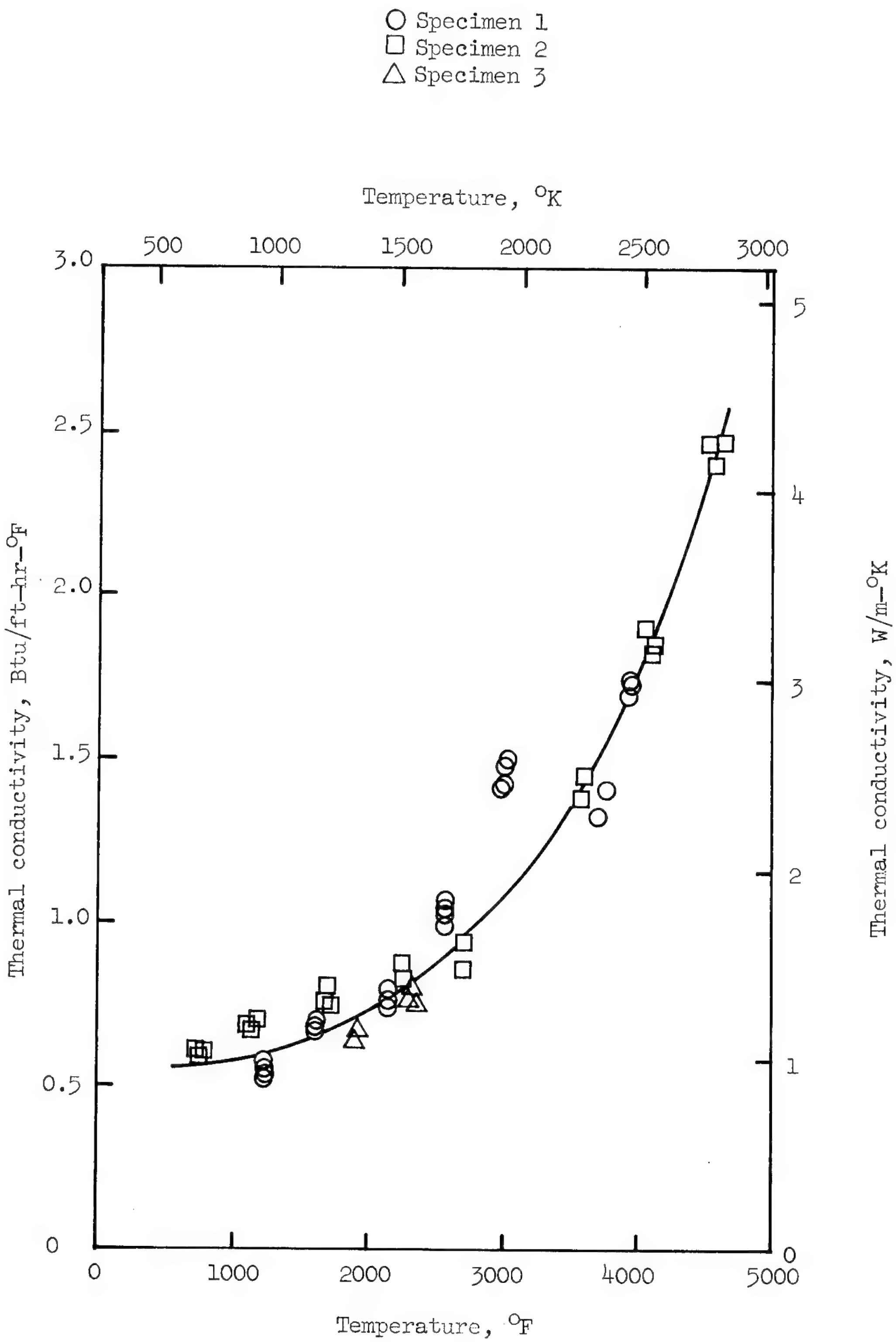


Figure 20.- Thermal conductivity of high-density phenolic-nylon char (SRI).

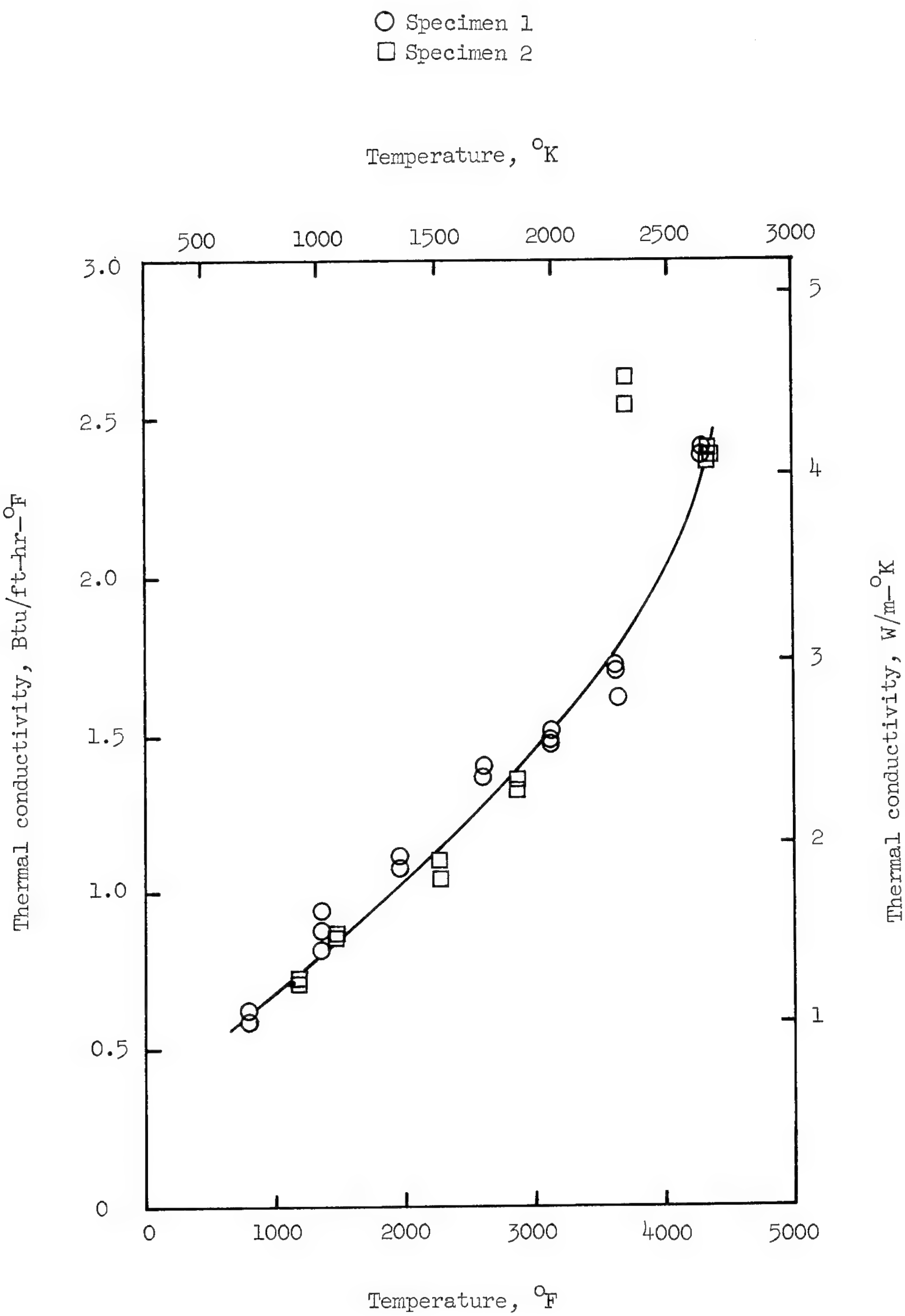


Figure 21.- Thermal conductivity of low-density phenolic-nylon char (SRI).

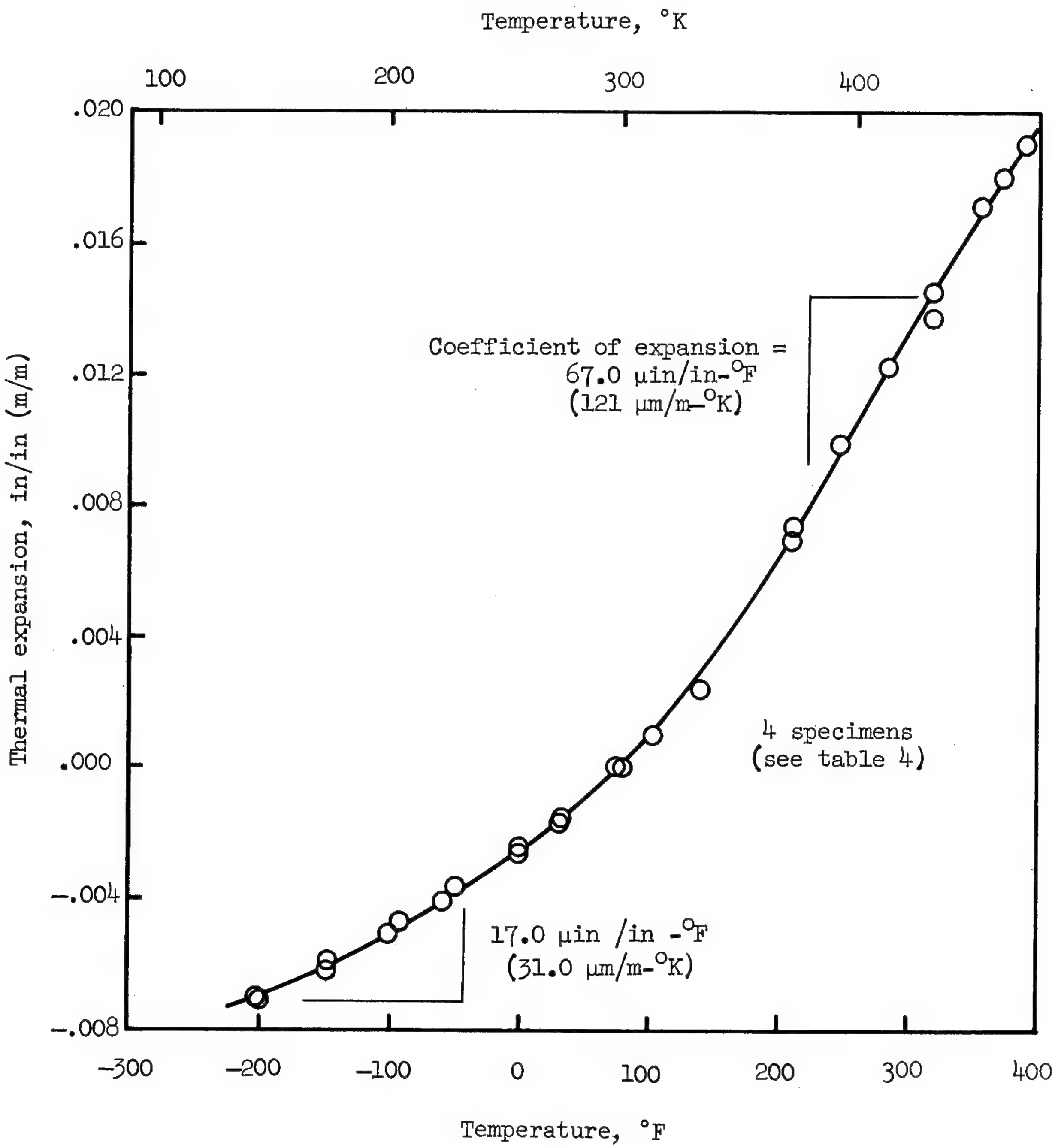


Figure 22.- Linear thermal expansion of high-density phenolic-nylon (Melpar).

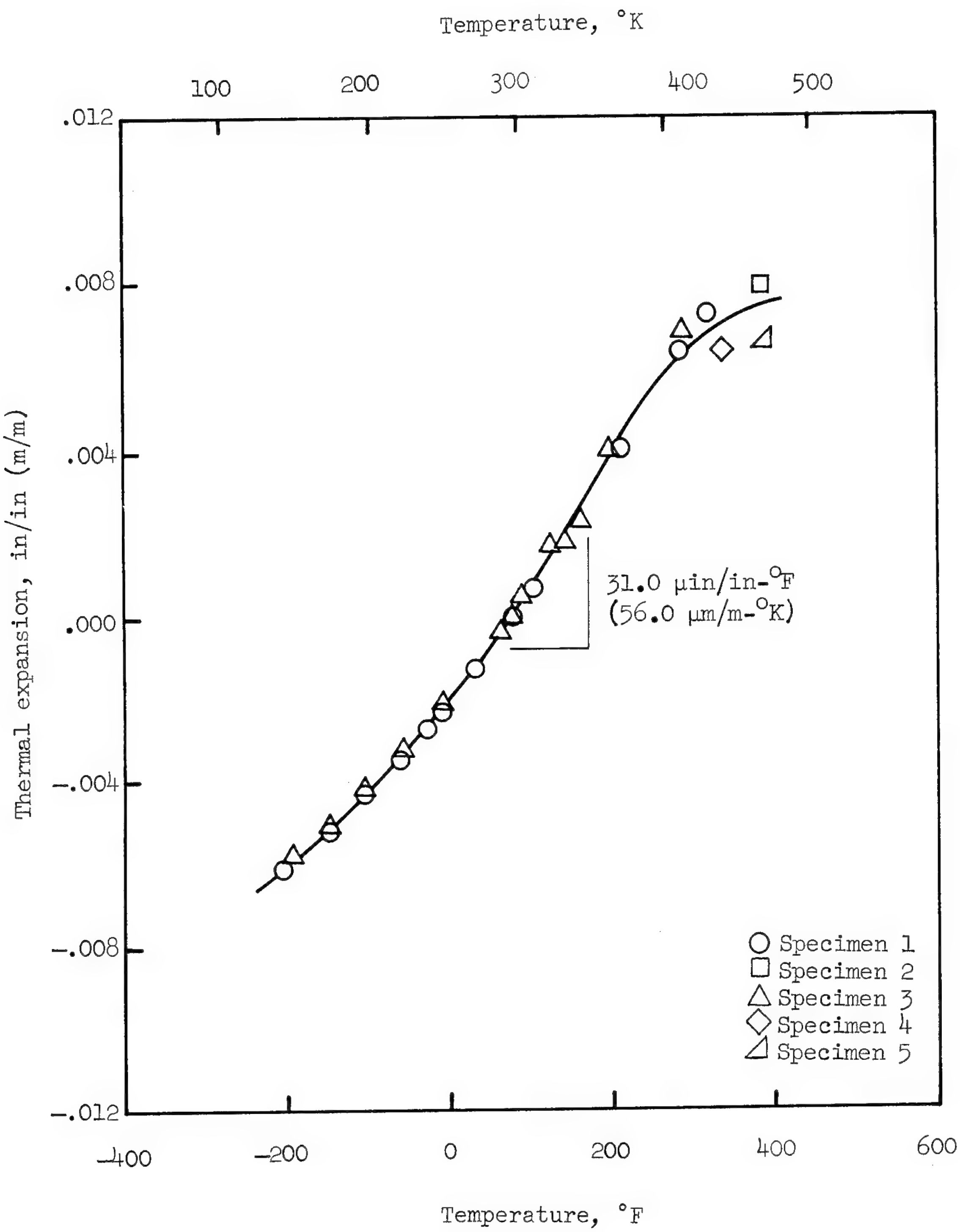
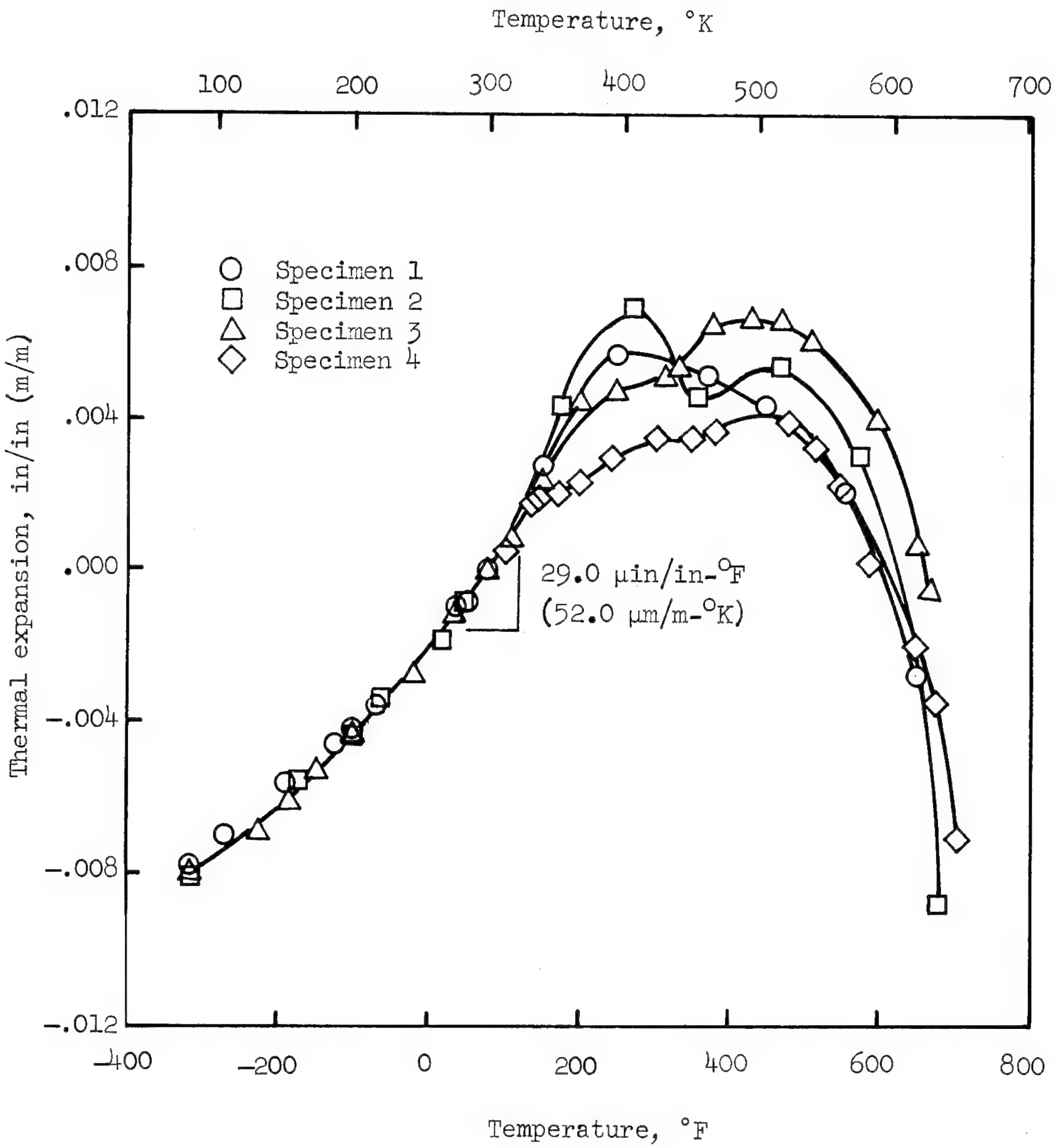


Figure 23.- Linear thermal expansion of low-density phenolic-nylon (Melpar).



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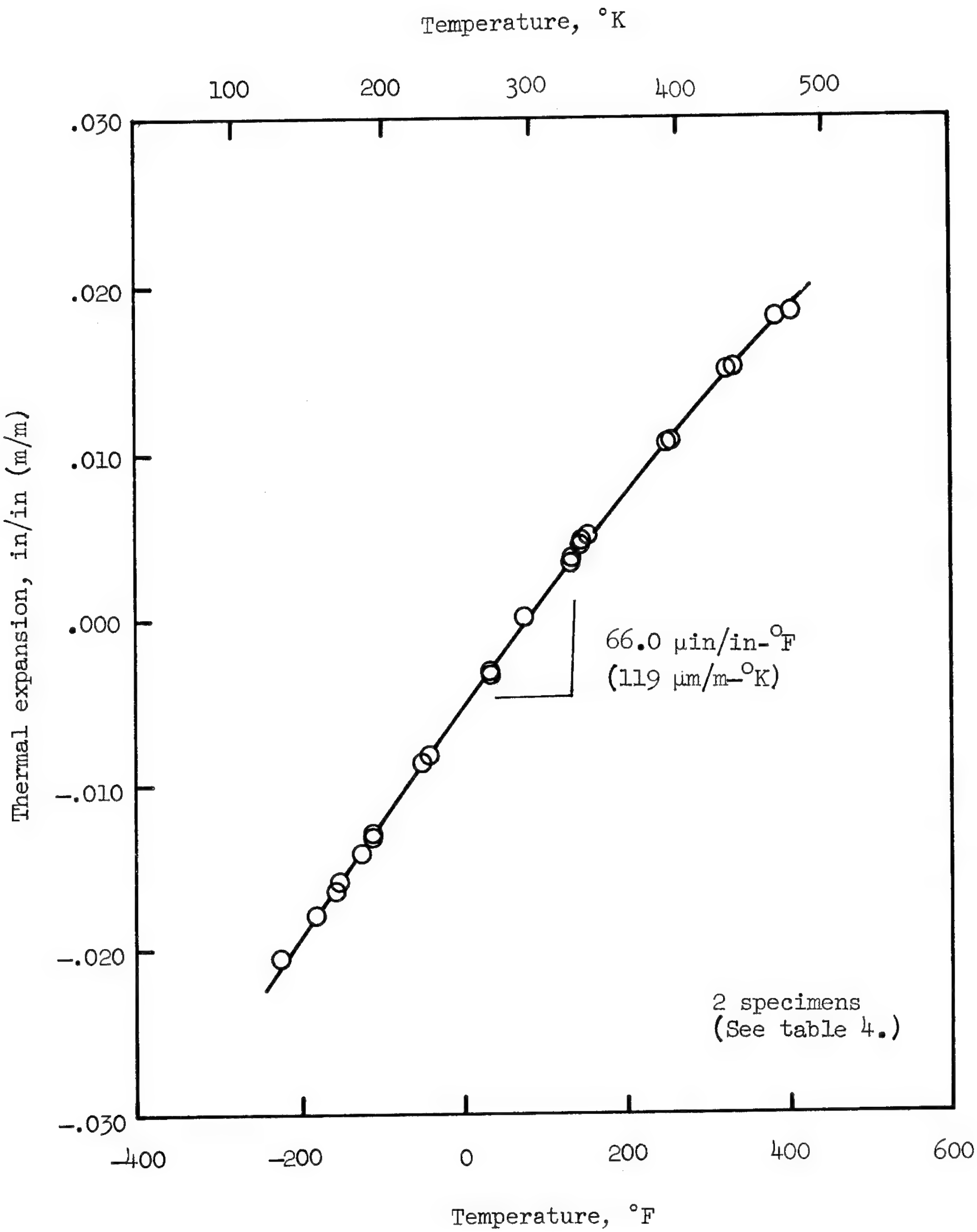


Figure 25.- Linear thermal expansion of filled silicone resin (Melpar).

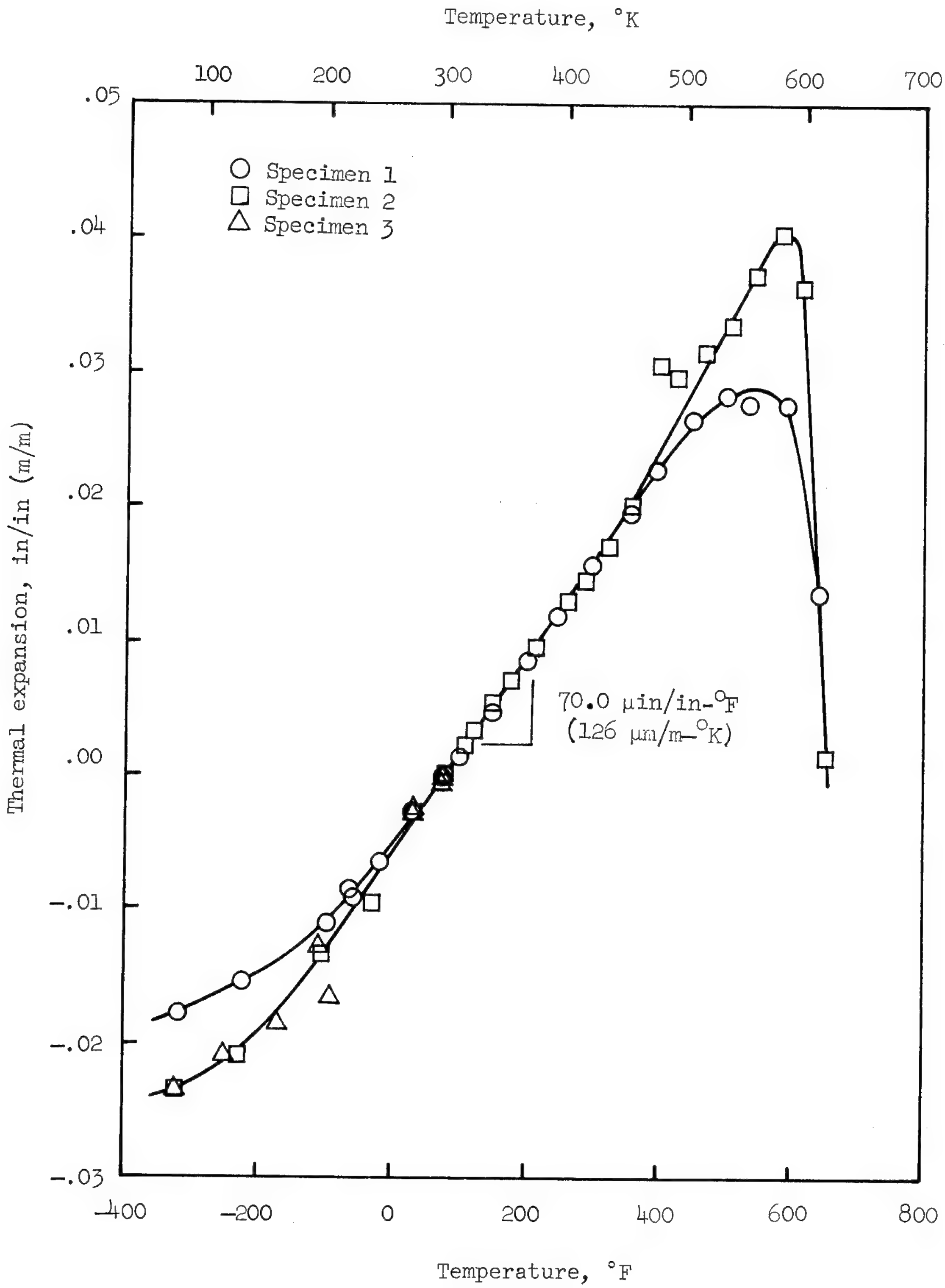


Figure 26.- Linear thermal expansion of filled silicone resin (SRI).

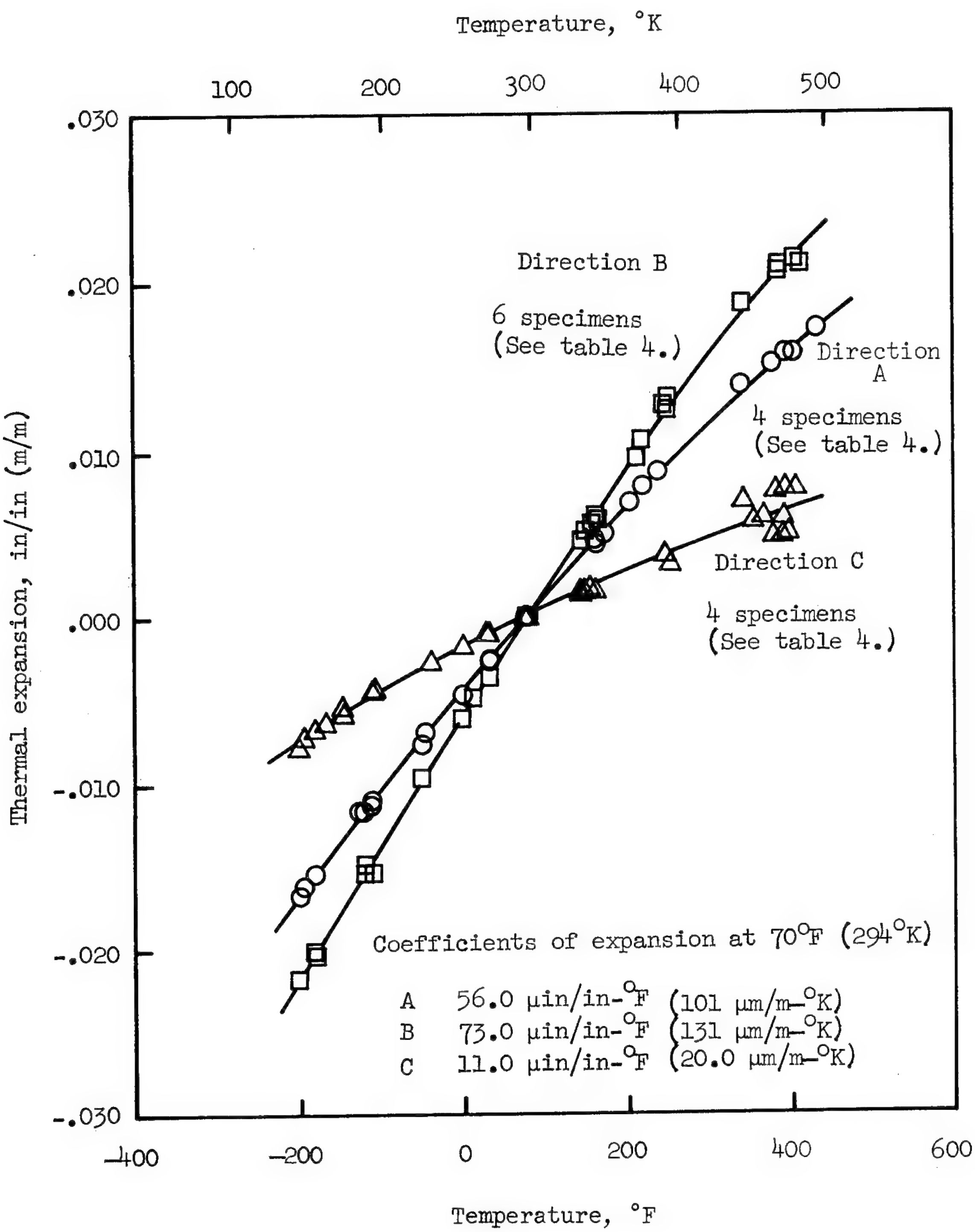


Figure 27.- Linear thermal expansion of filled silicone resin in honeycomb (Melpar).

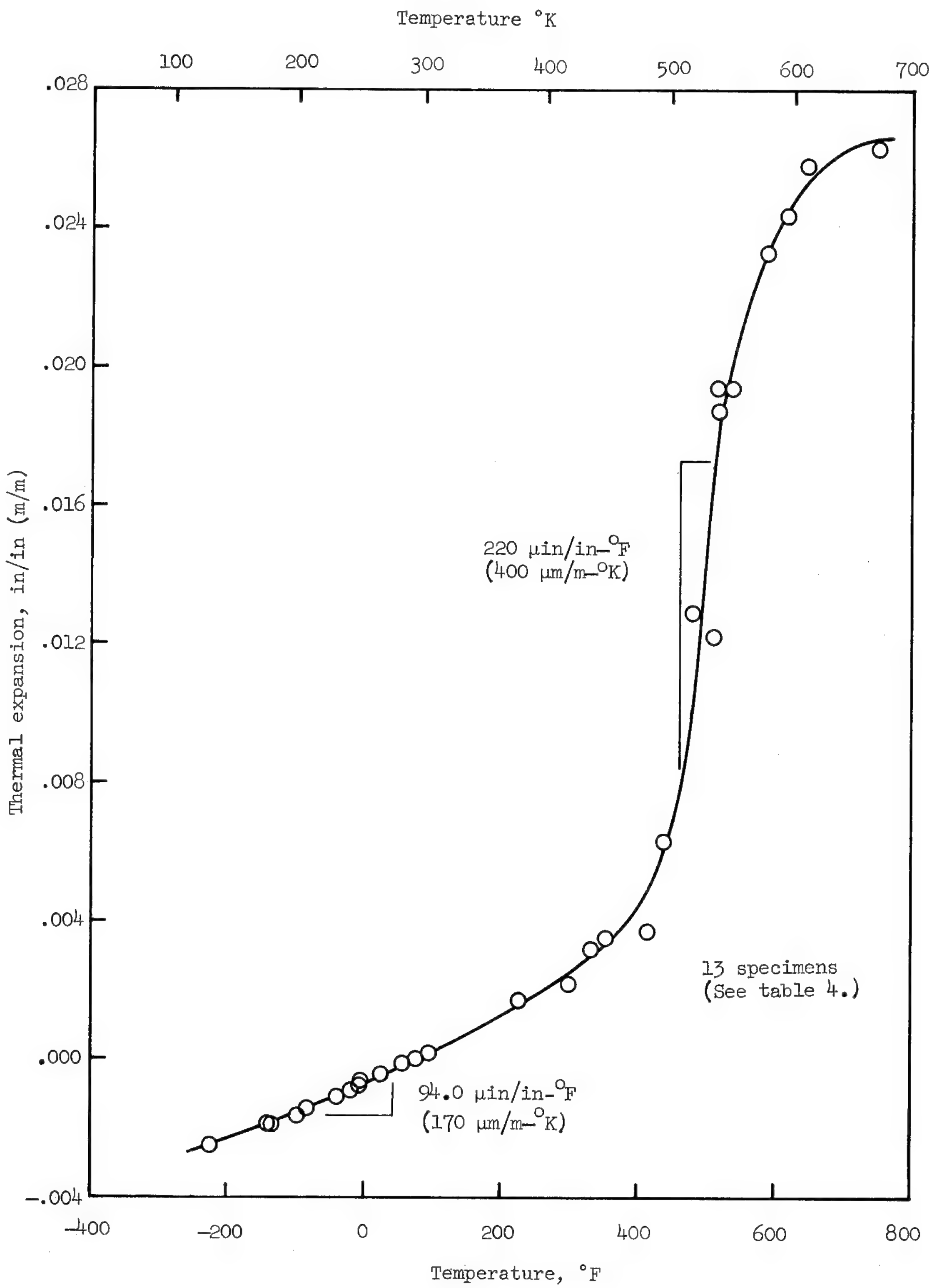
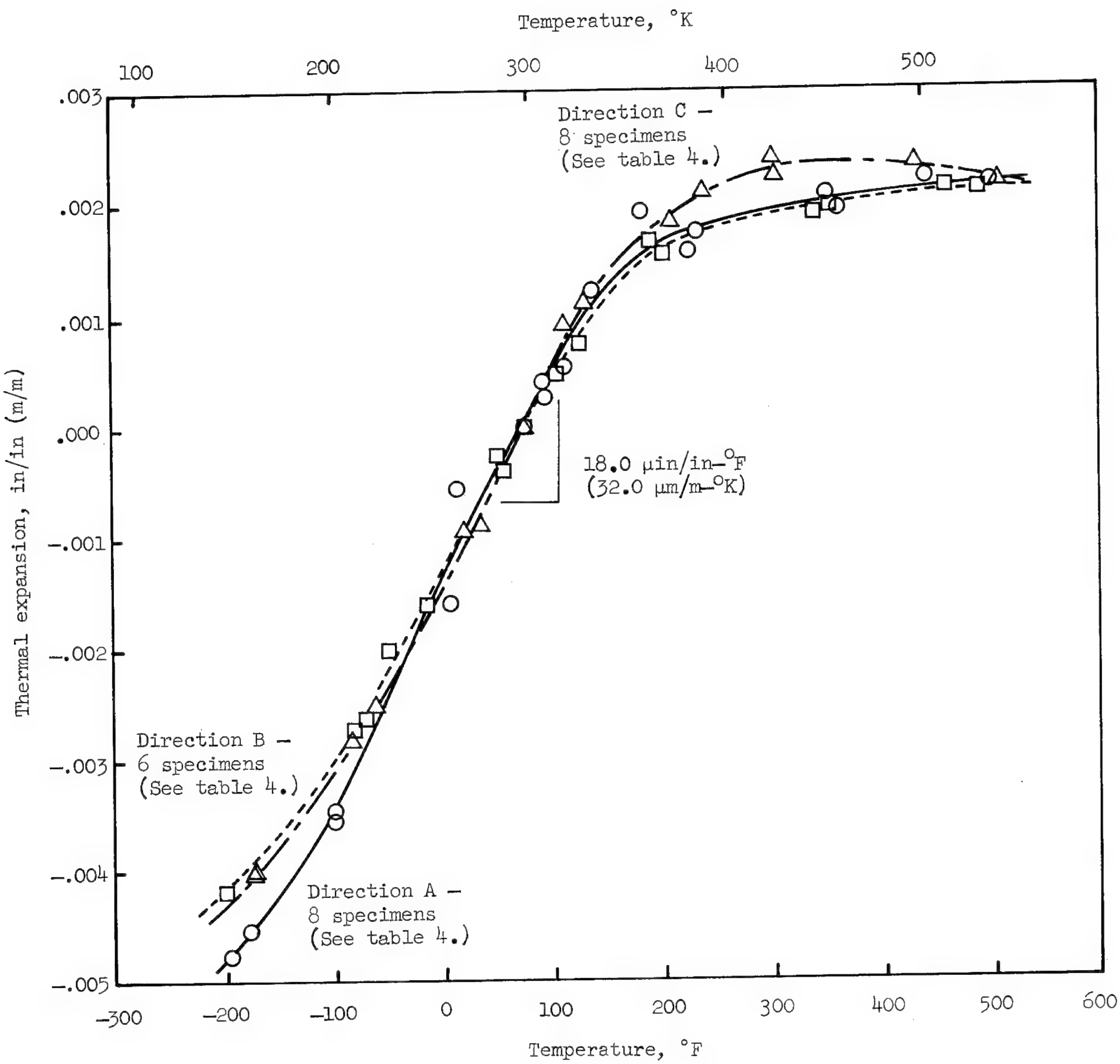


Figure 28.- Linear thermal expansion of Narmco 4028 carbon-fiber-reinforced phenolic (Melpar).



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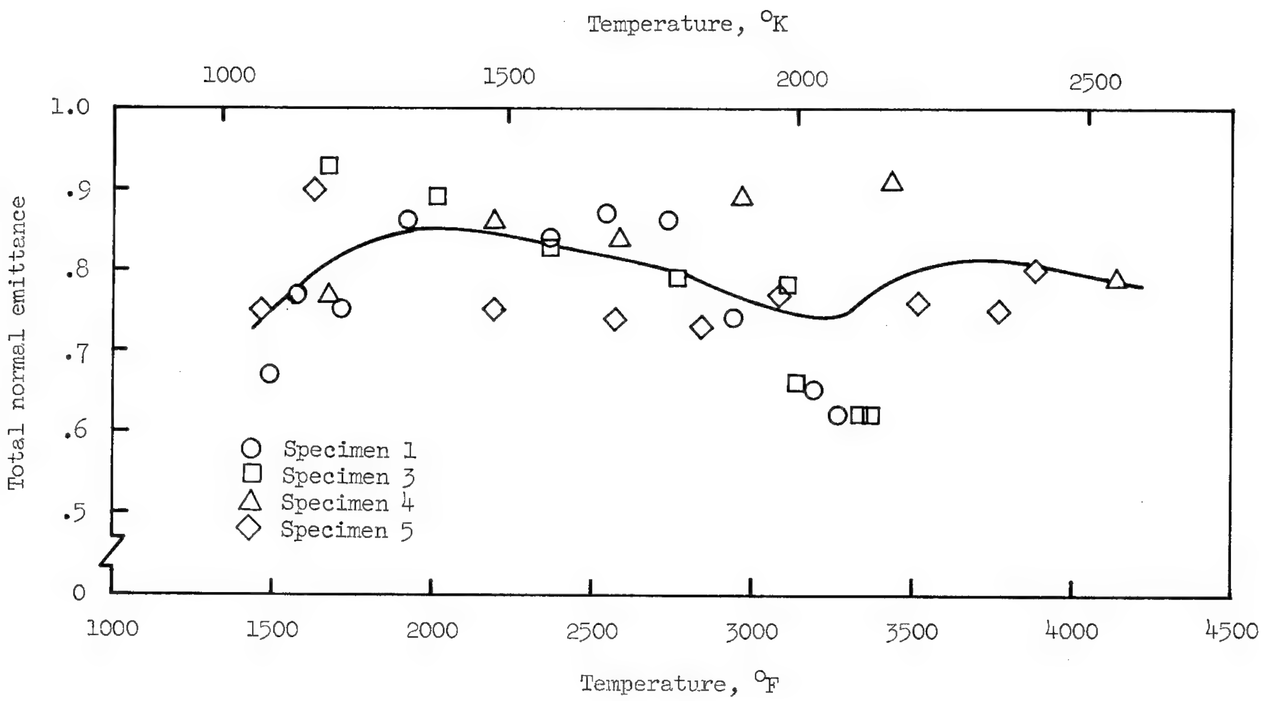


Figure 30.- Total normal emittance of high-density phenolic-nylon char (SRI).

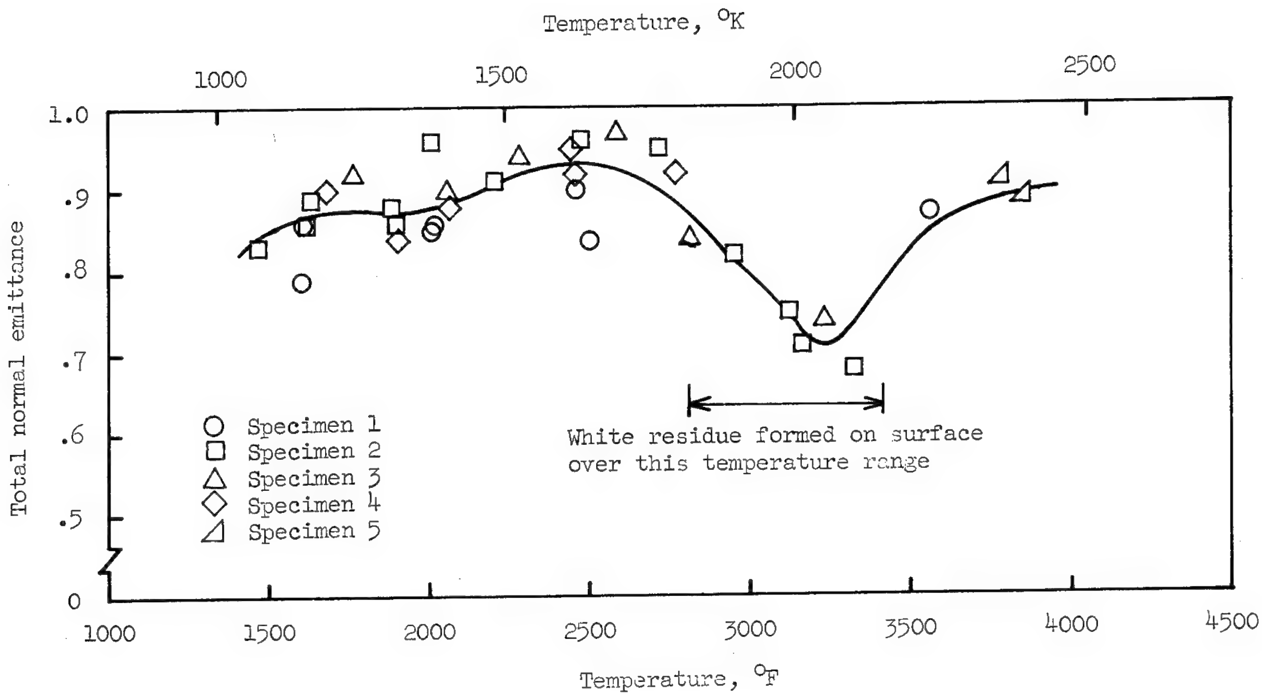
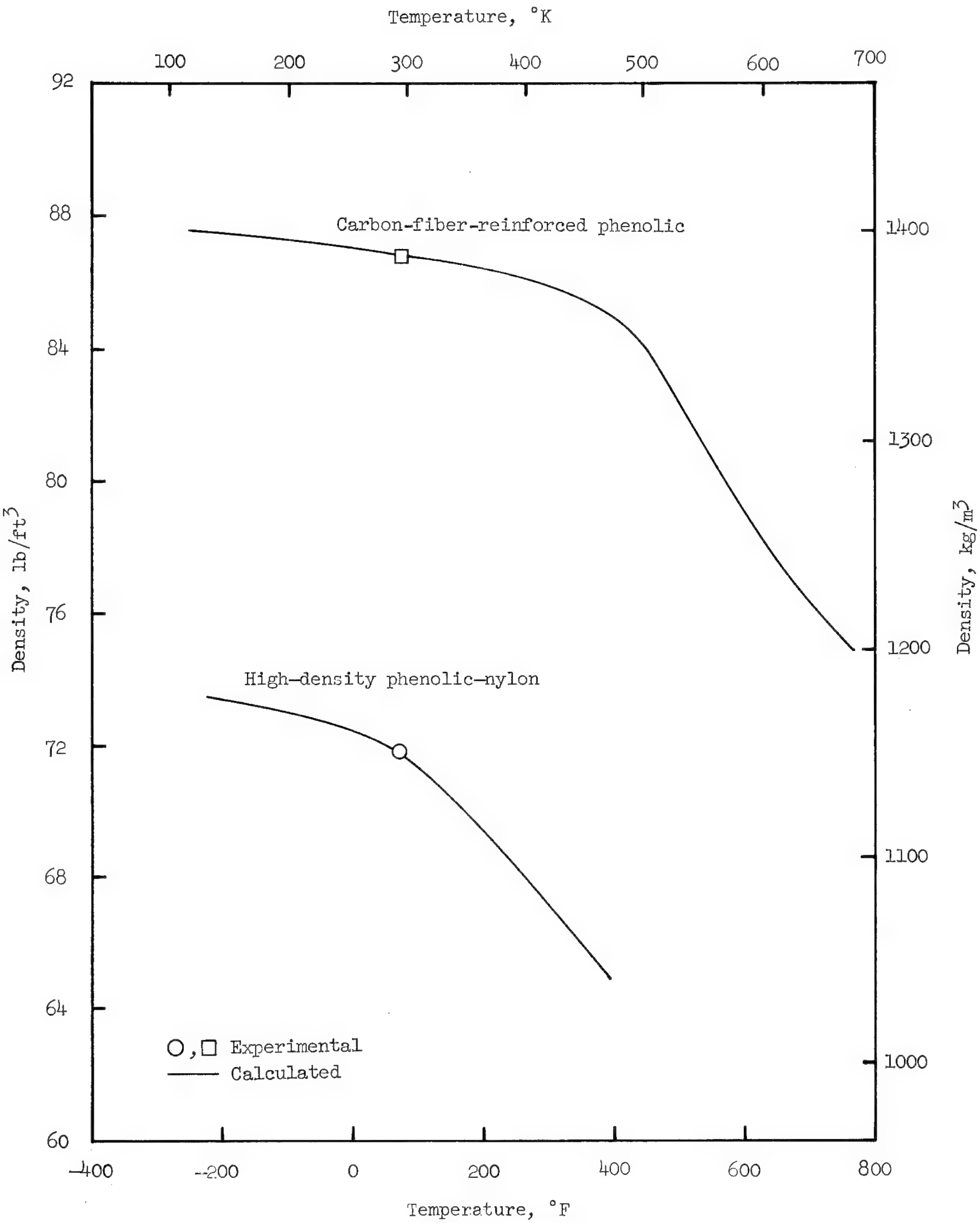


Figure 31.- Total normal emittance of low-density phenolic-nylon char (SRI).



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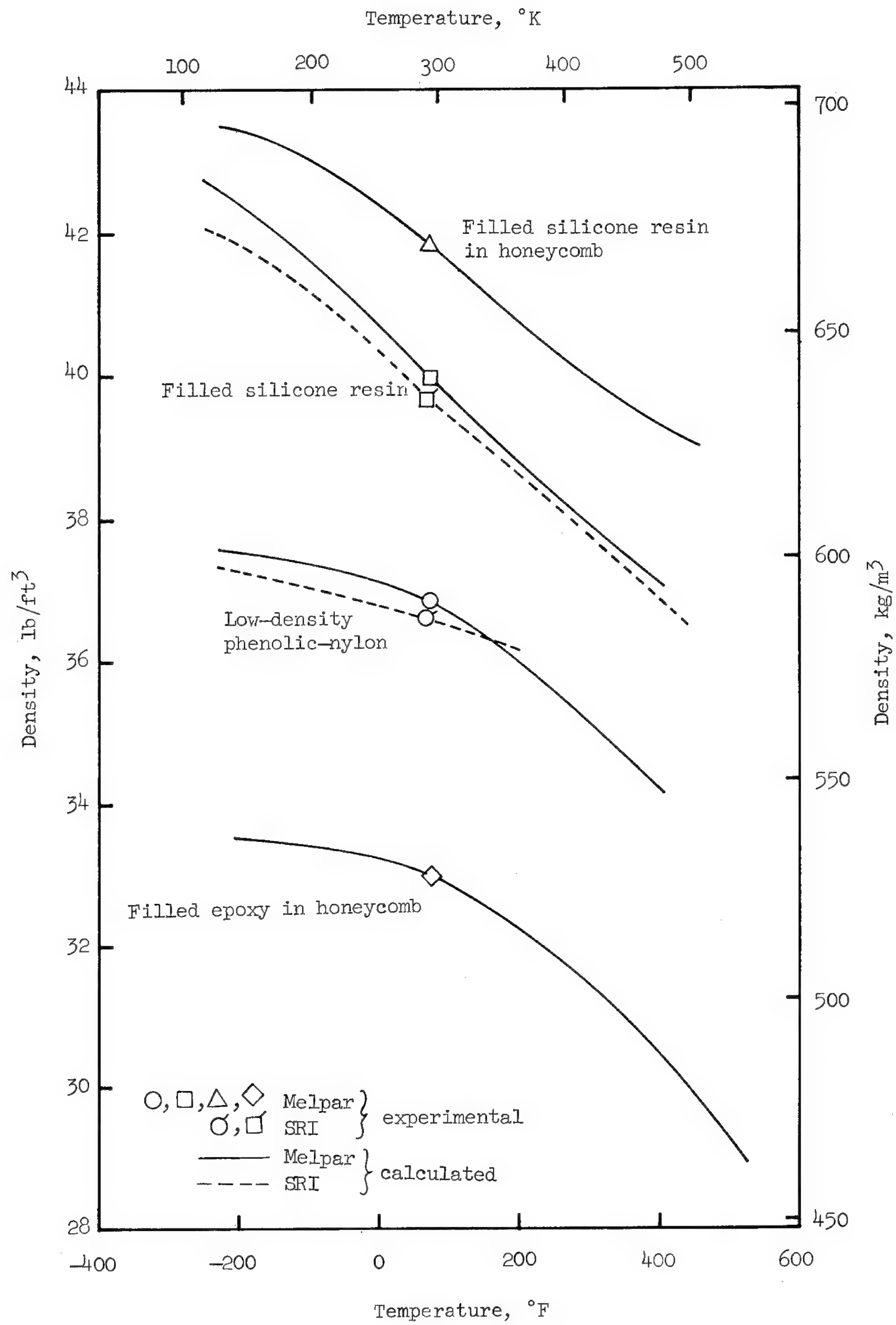


Figure 33.- Density of low-density phenolic-nylon, filled silicone resin, and Avcoat 5026-39-HC G filled epoxy in honeycomb.

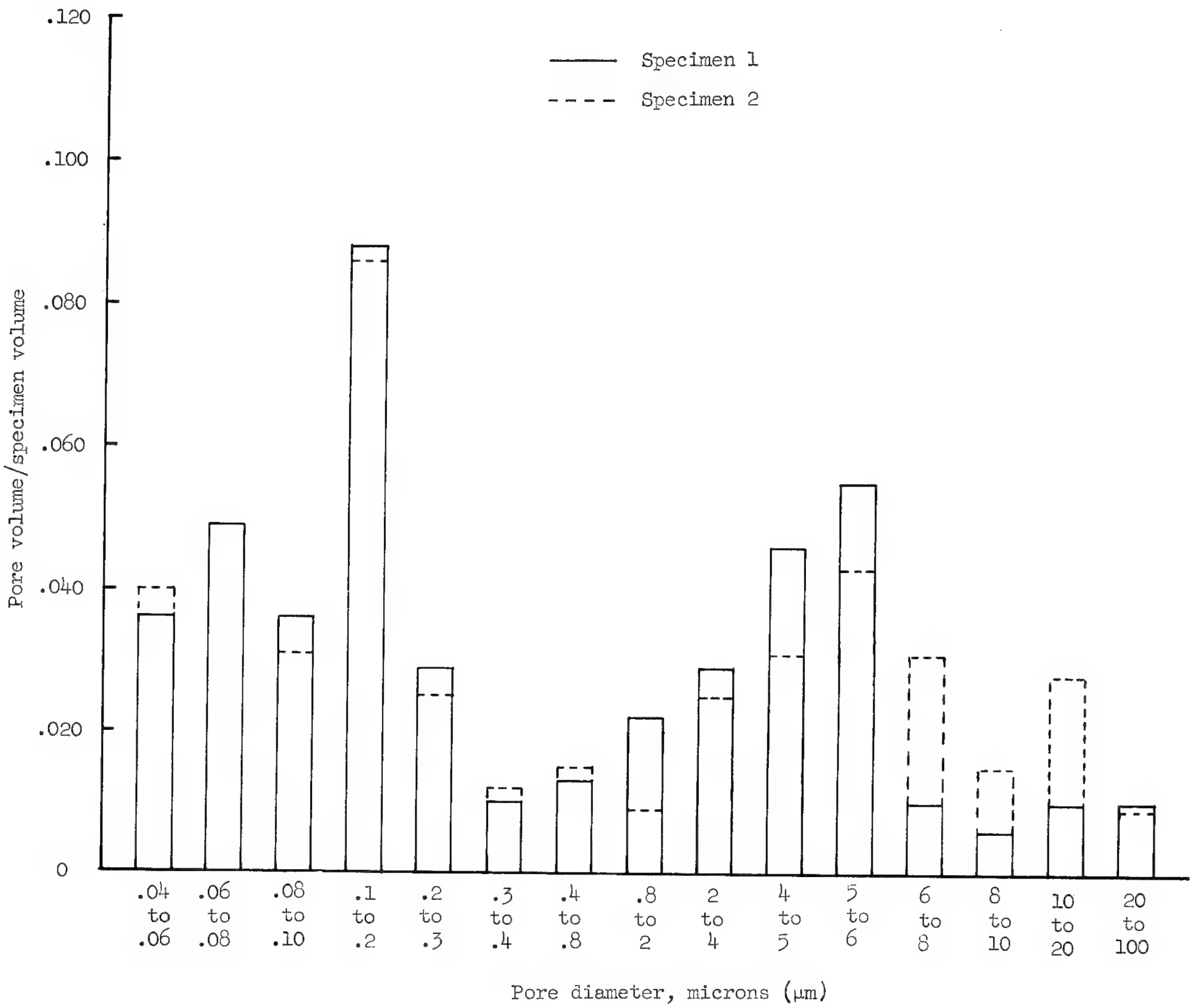


Figure 34.- Pore spectrum for low-density phenolic-nylon (NASA).

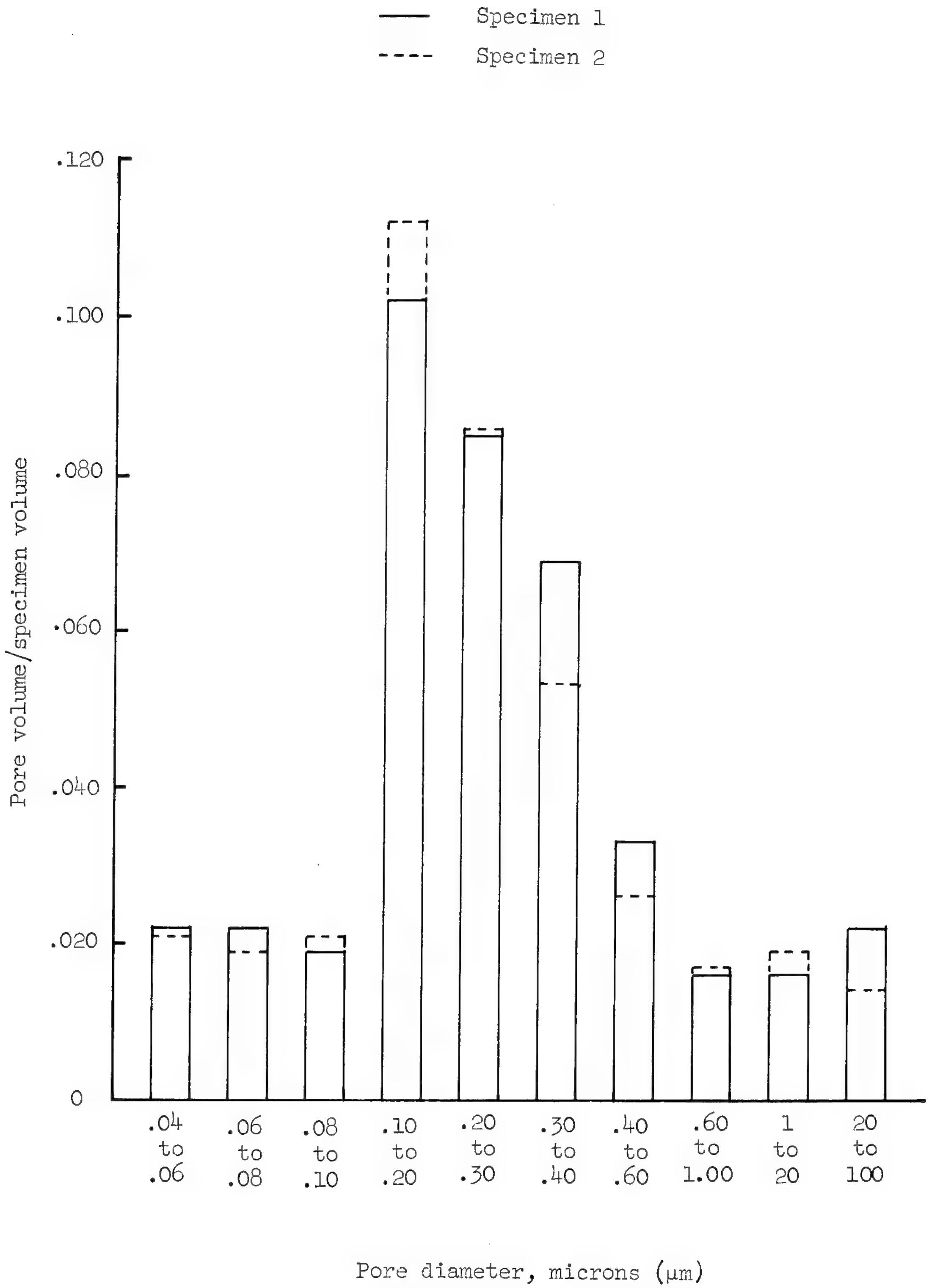


Figure 35.- Pore spectrum for filled silicone resin (NASA).

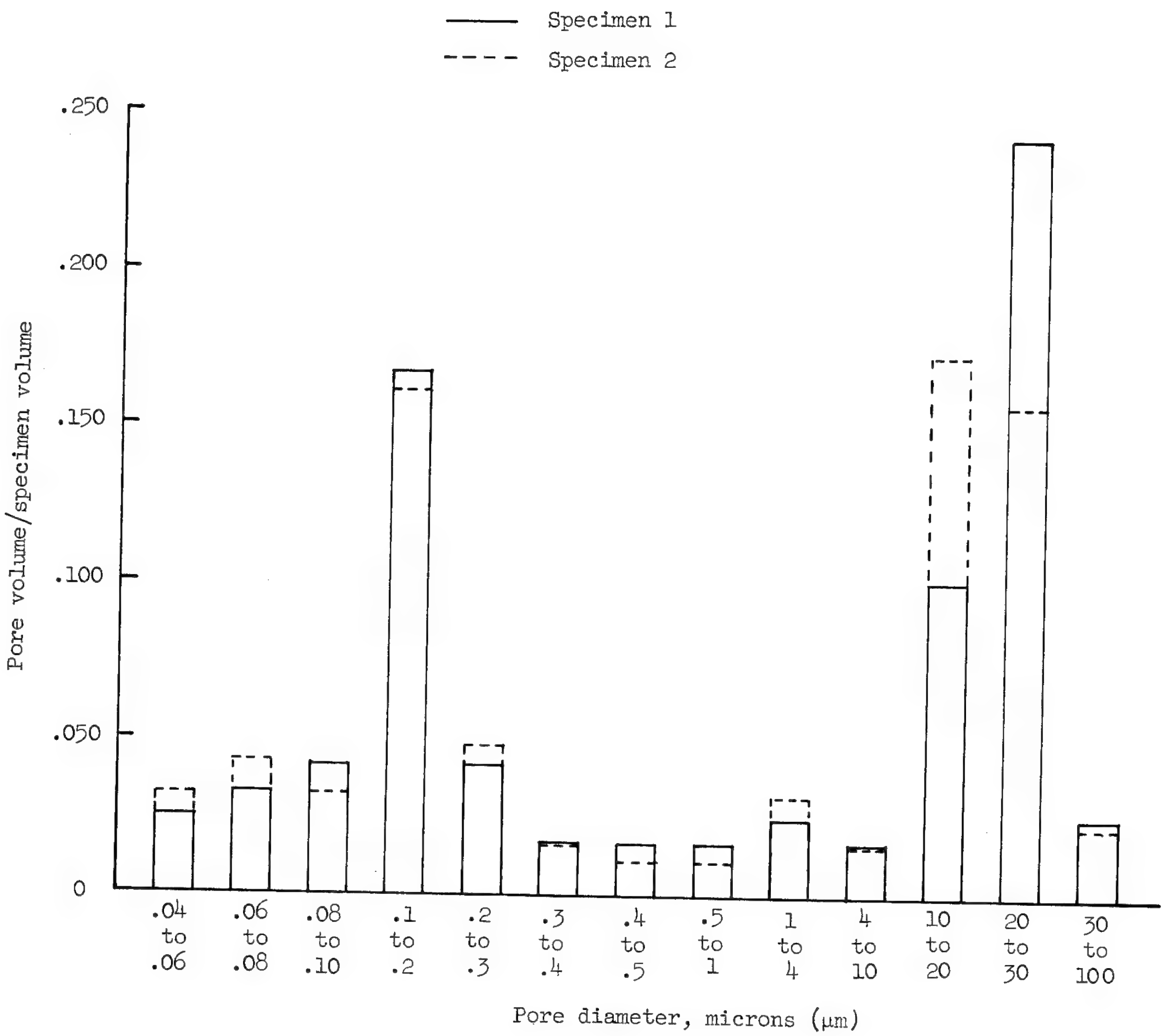


Figure 36.- Pore spectrum for Avcoat 5026-39-HC G filled epoxy in honeycomb (NASA).

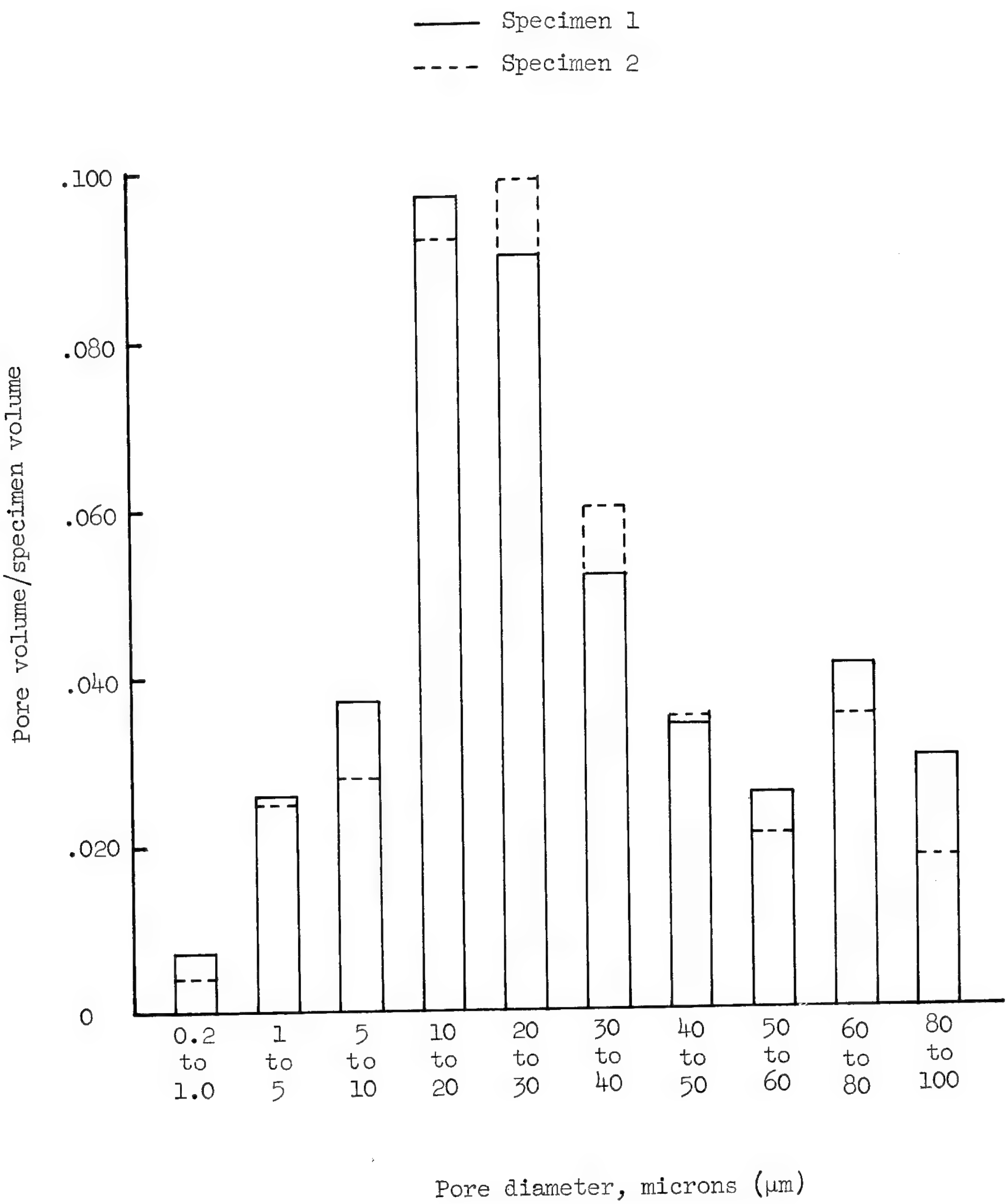


Figure 37.- Pore spectrum for high-density phenolic-nylon char (NASA).

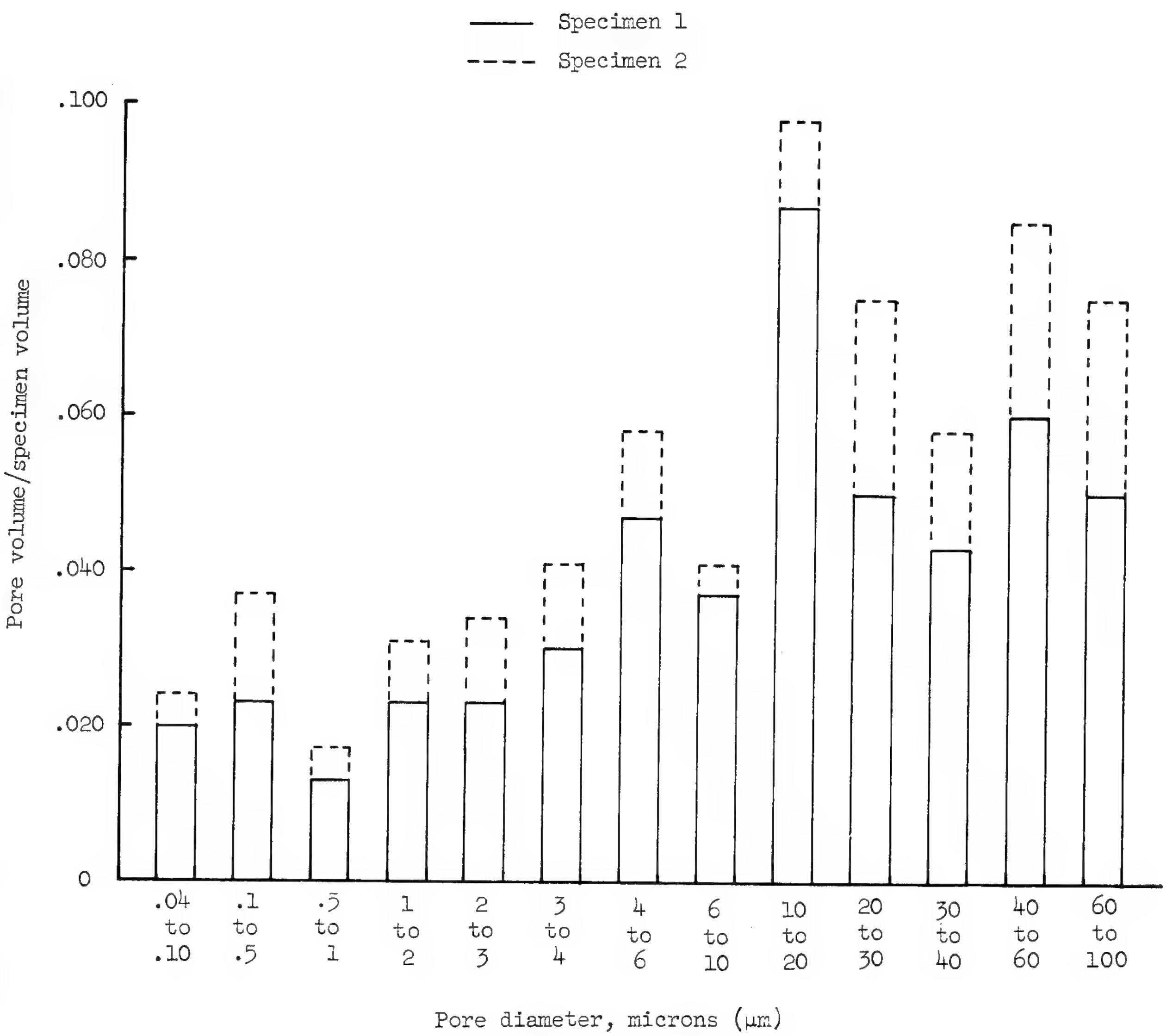
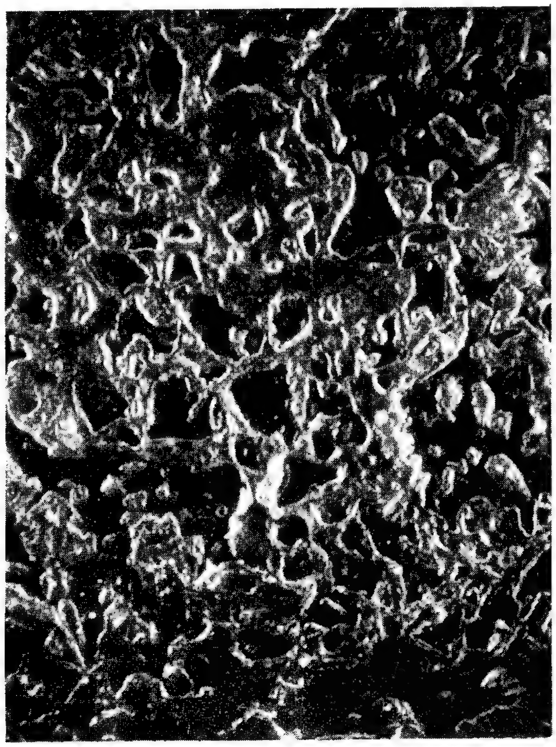


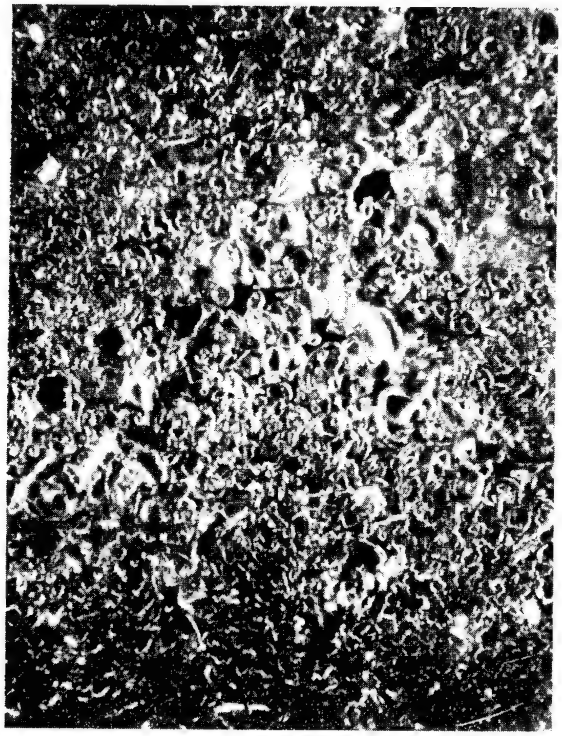
Figure 38.- Pore spectrum for low-density phenolic-nylon char (NASA).



(a) Cross section taken on plane perpendicular to thickness direction.

(b) Cross section through thickness direction. L-65-119

Figure 39.- Photomicrographs at ×100 magnification of high-density phenolic-nylon char (SRI).



(a) Cross section taken on plane perpendicular to thickness direction.

(b) Cross section through thickness direction.

L-65-120

Figure 40.- Photomicrographs at ×100 magnification of low-density phenolic-nylon char (SRI).

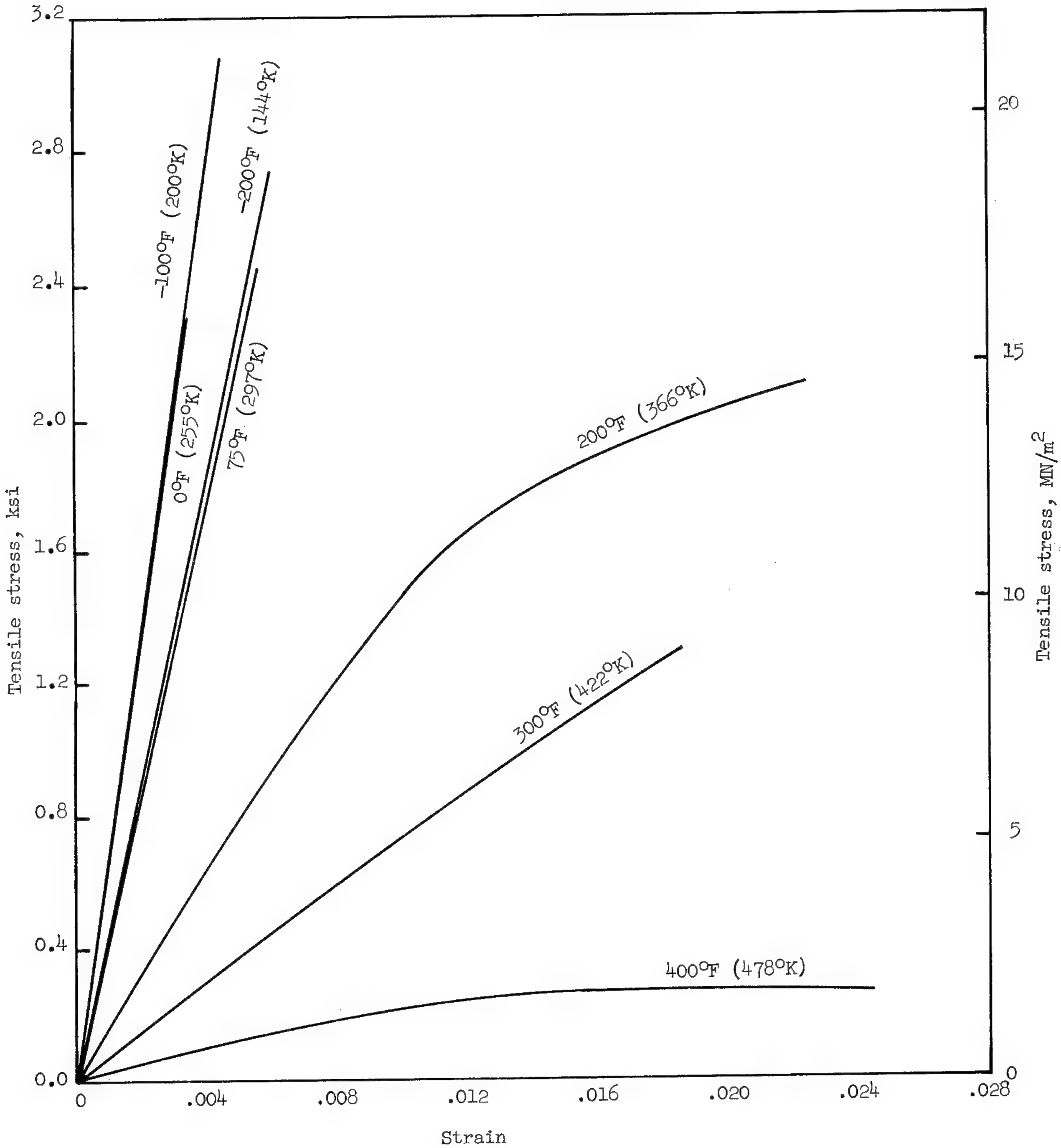


Figure 41.- Tensile stress-strain curves for high-density phenolic-nylon (Melpar).

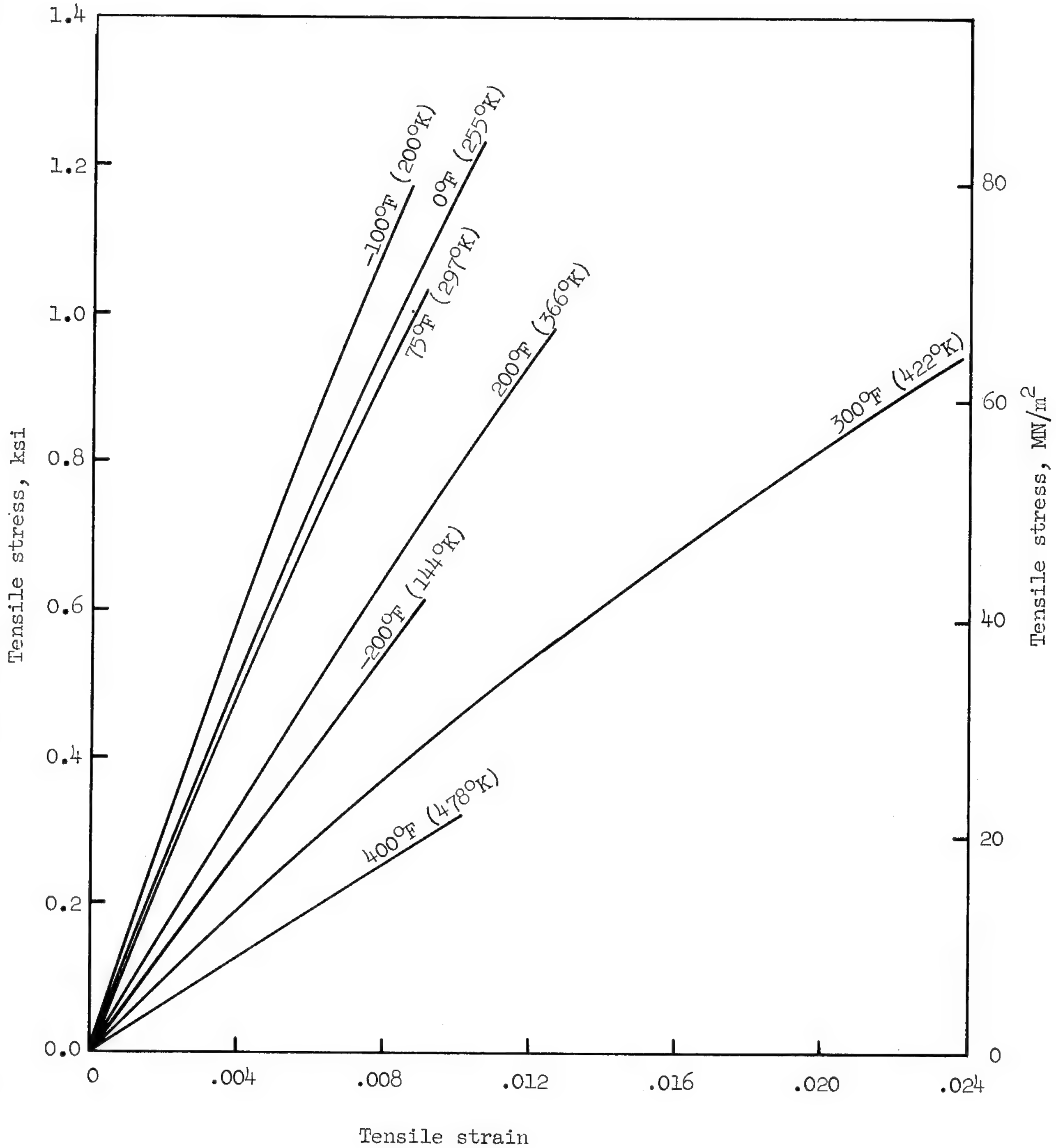


Figure 42.- Tensile stress-strain curves for low-density phenolic-nylon (Melpar).

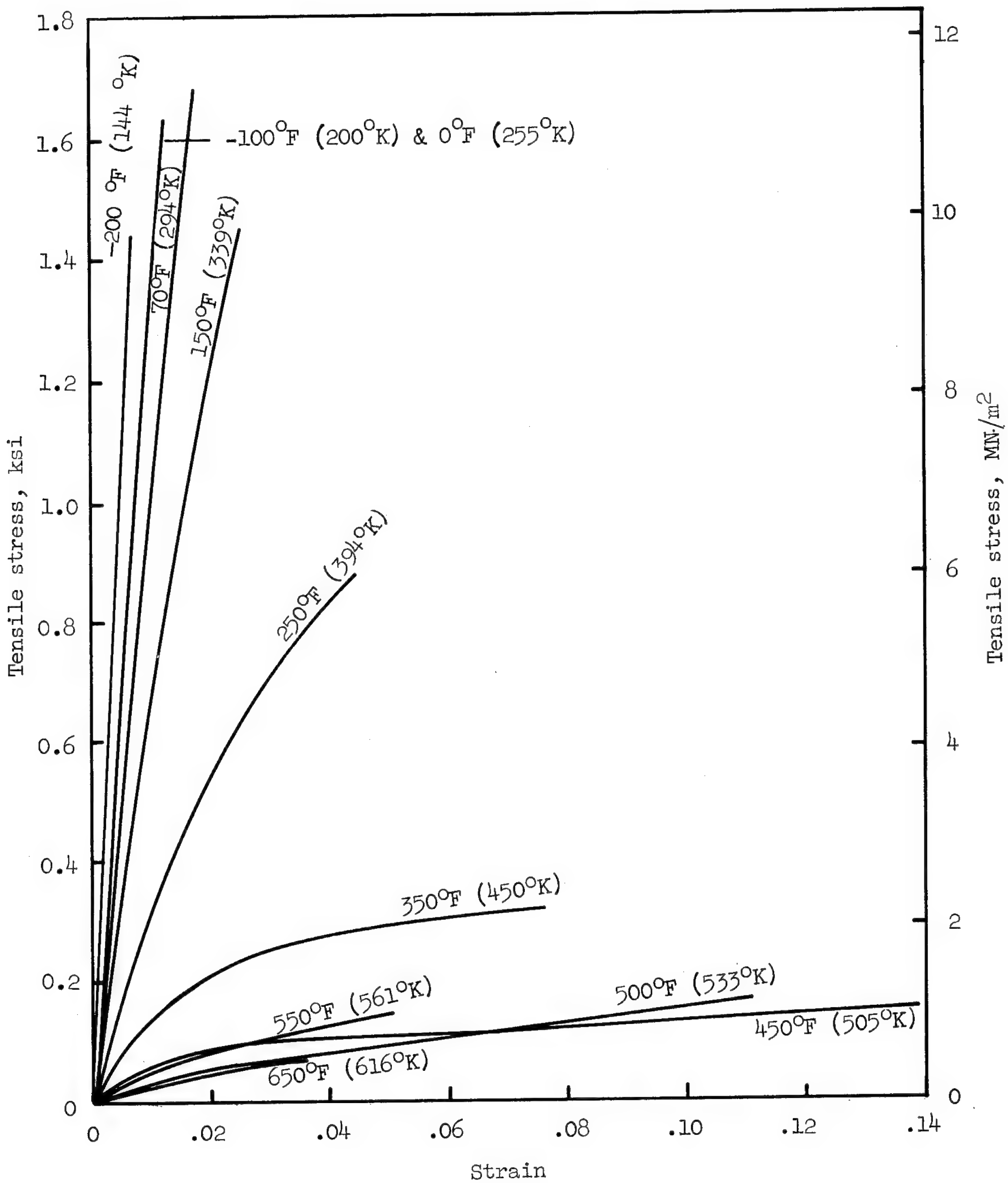


Figure 43.- Tensile stress-strain curves for low-density phenolic-nylon (SRI).

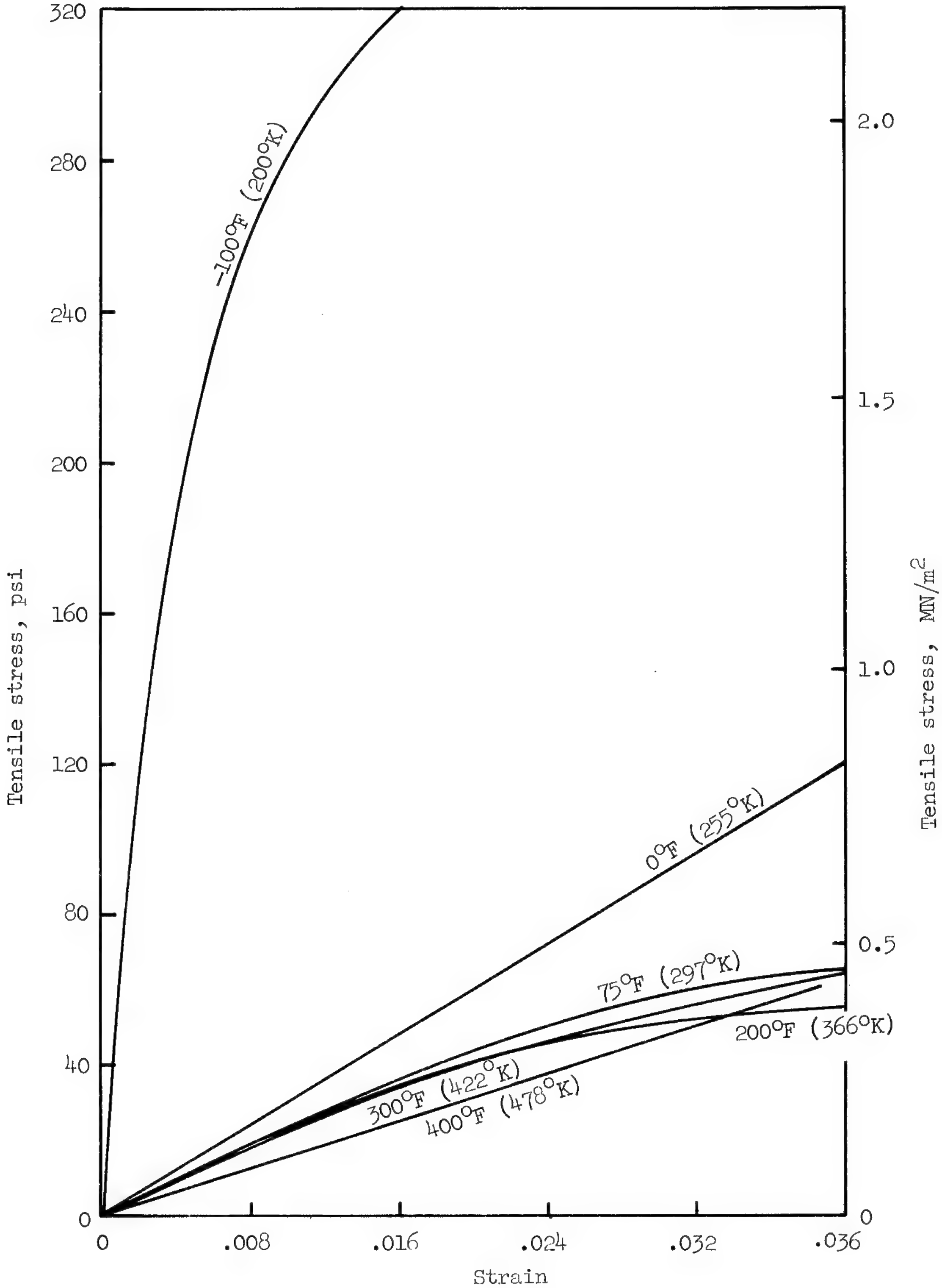


Figure 44.- Tensile stress-strain curves for filled silicone resin (Melpar).

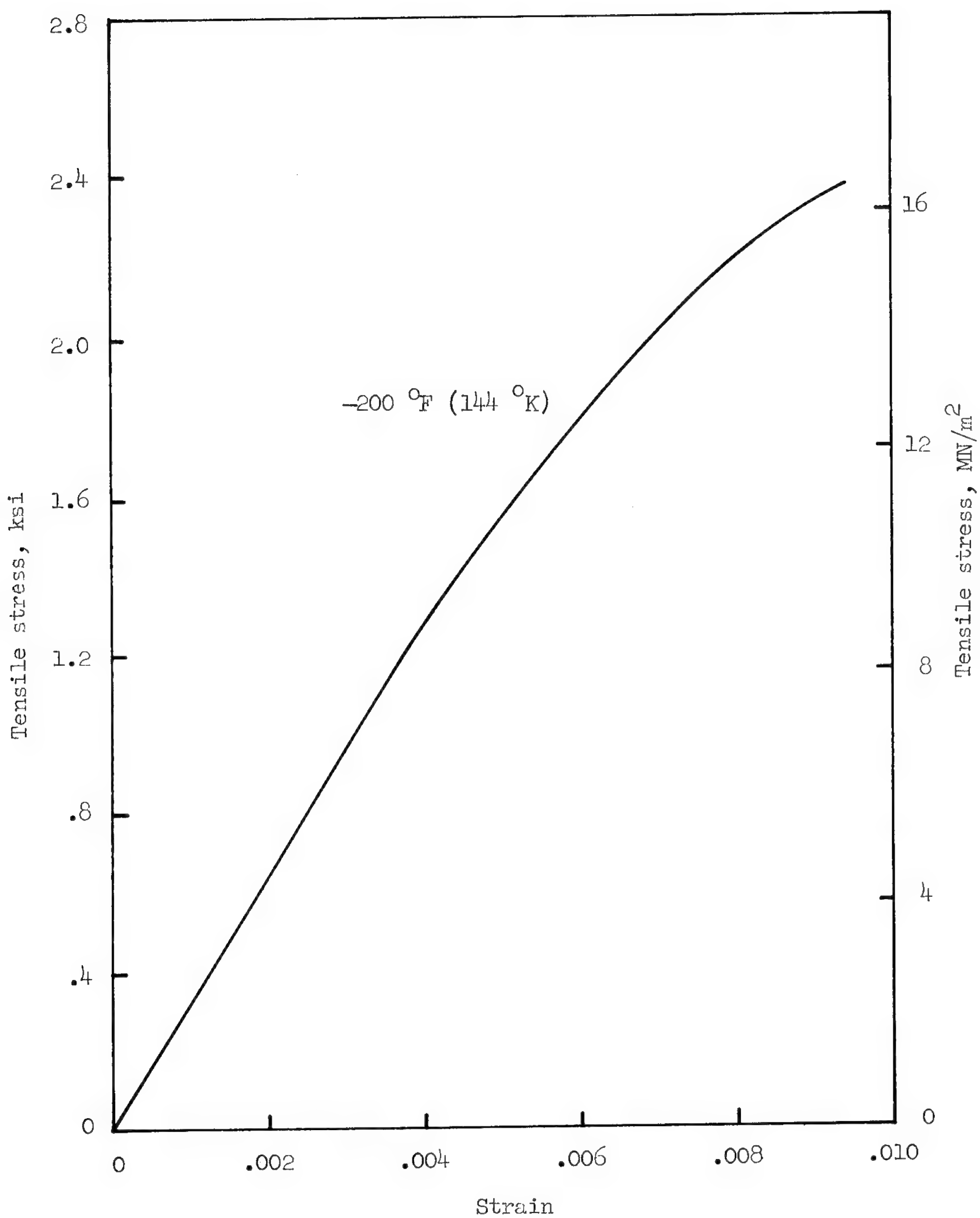


Figure 44.- Concluded.

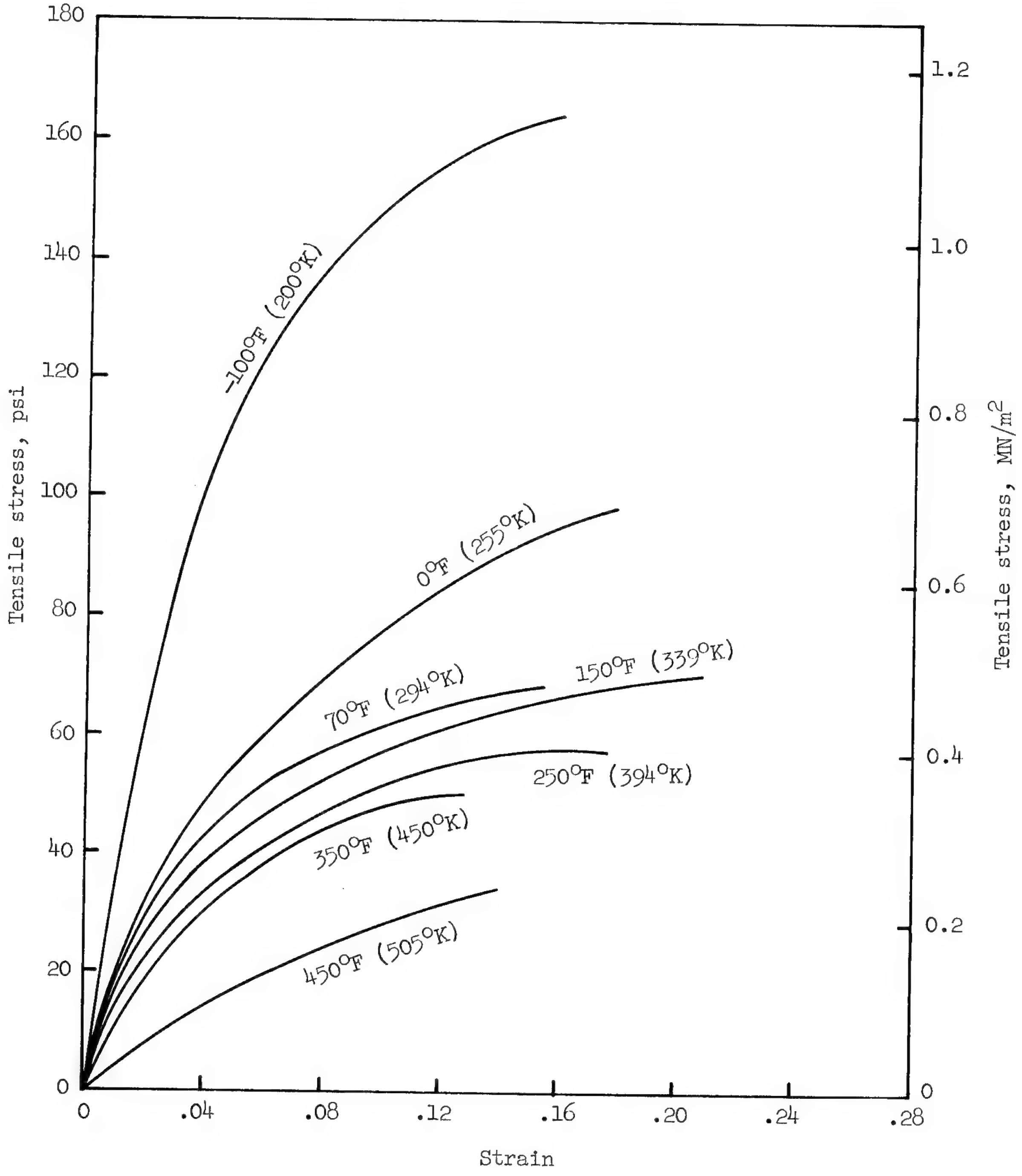


Figure 45.- Tensile stress-strain curves for filled silicone resin (SRI).

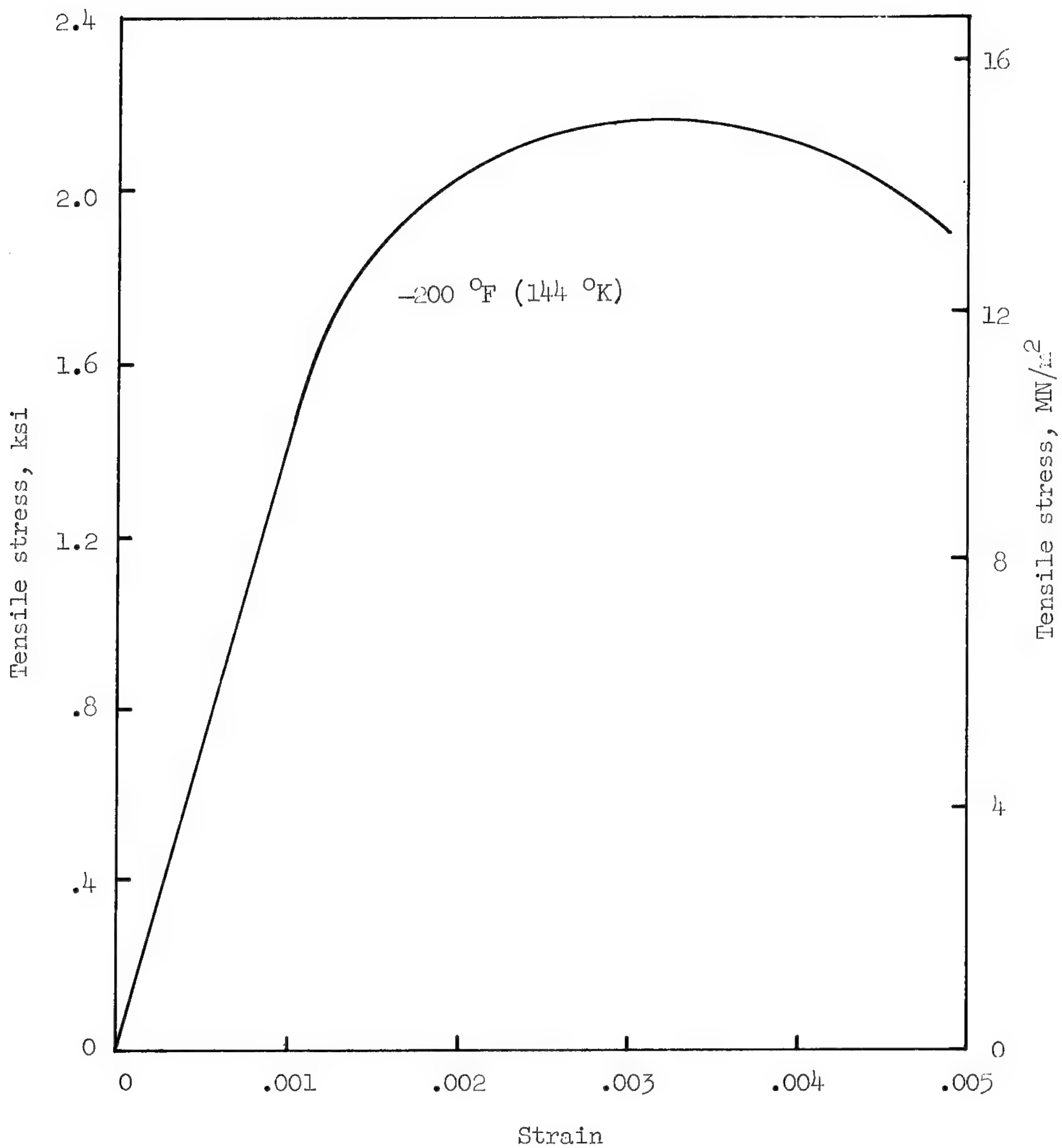


Figure 45.- Concluded.

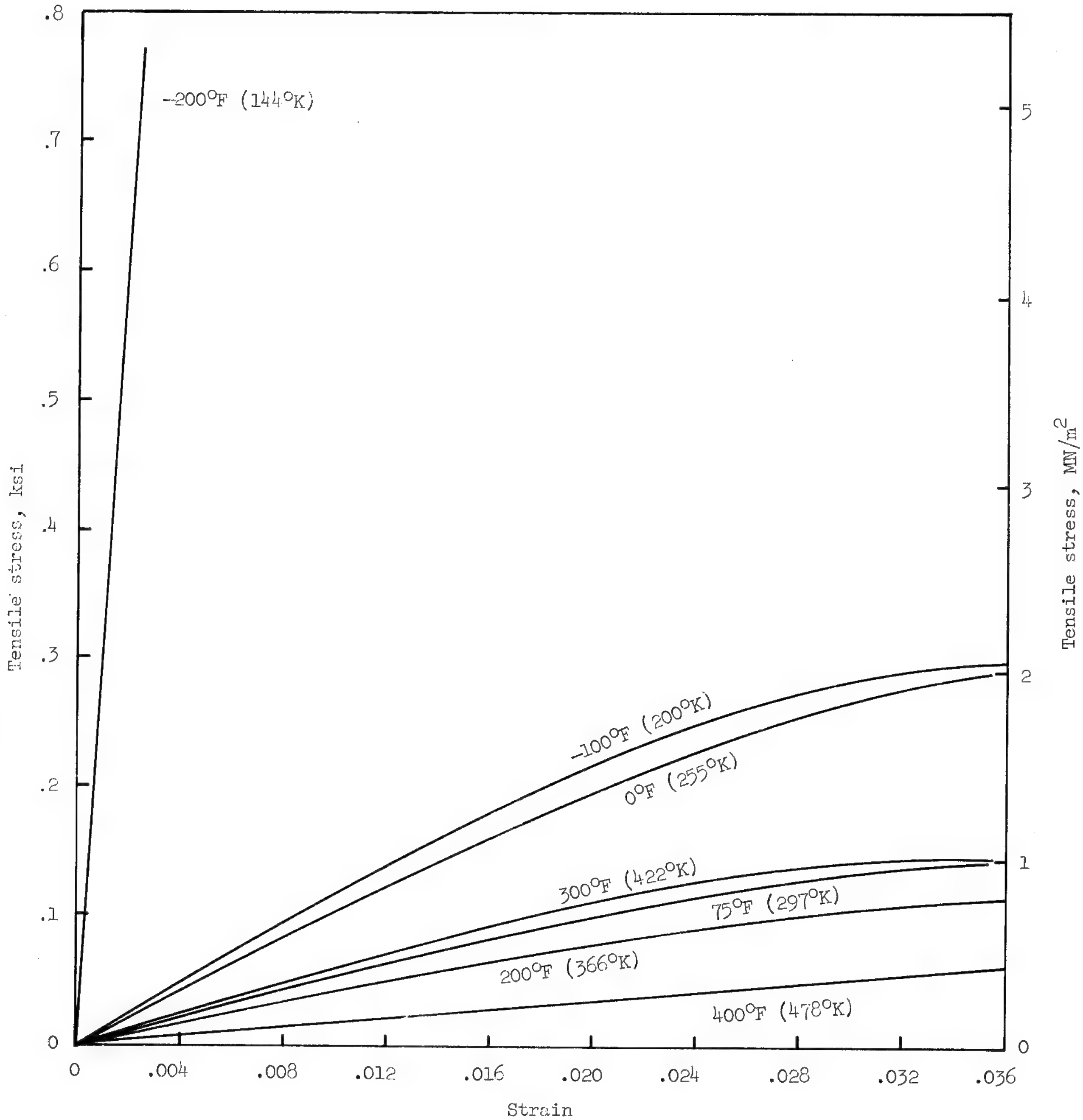


Figure 46.- Tensile stress-strain curves for filled silicone resin in honeycomb in direction A (Melpar).

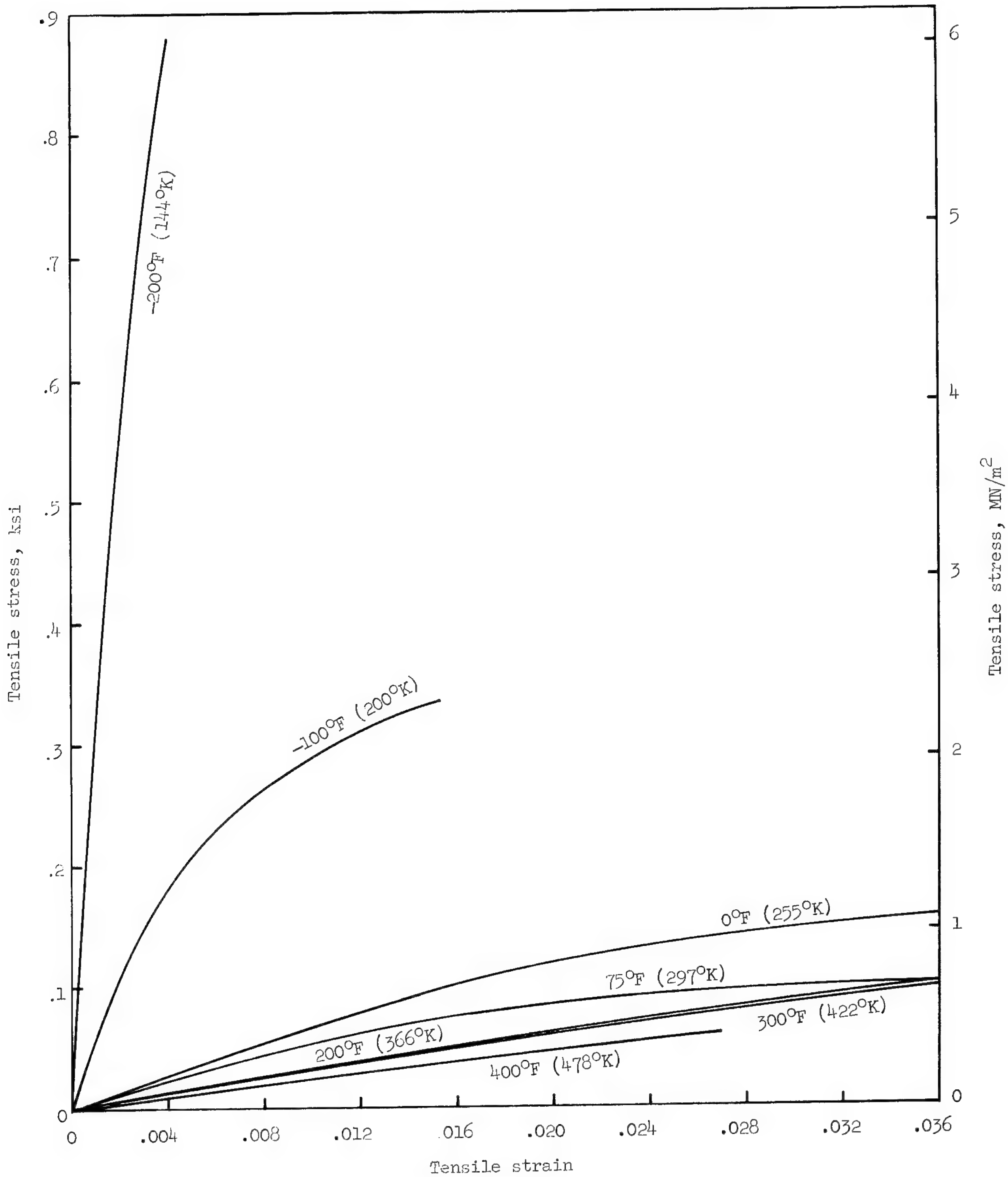


Figure 47.- Tensile stress-strain curves for filled silicone resin in honeycomb in direction B (Melpar).

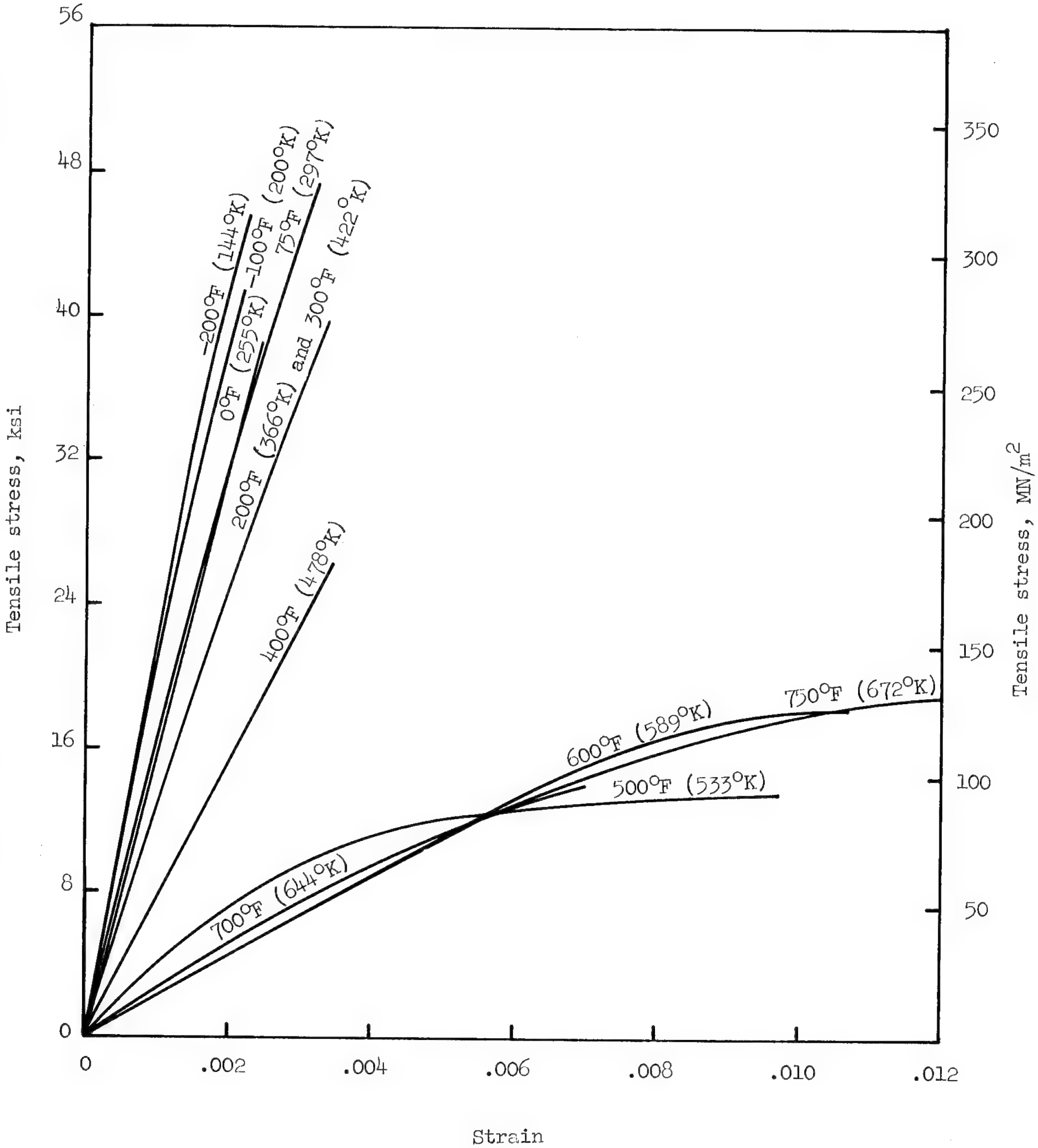


Figure 48.- Tensile stress-strain curves for Narmco 4028 carbon-fiber-reinforced phenolic (Melpar).

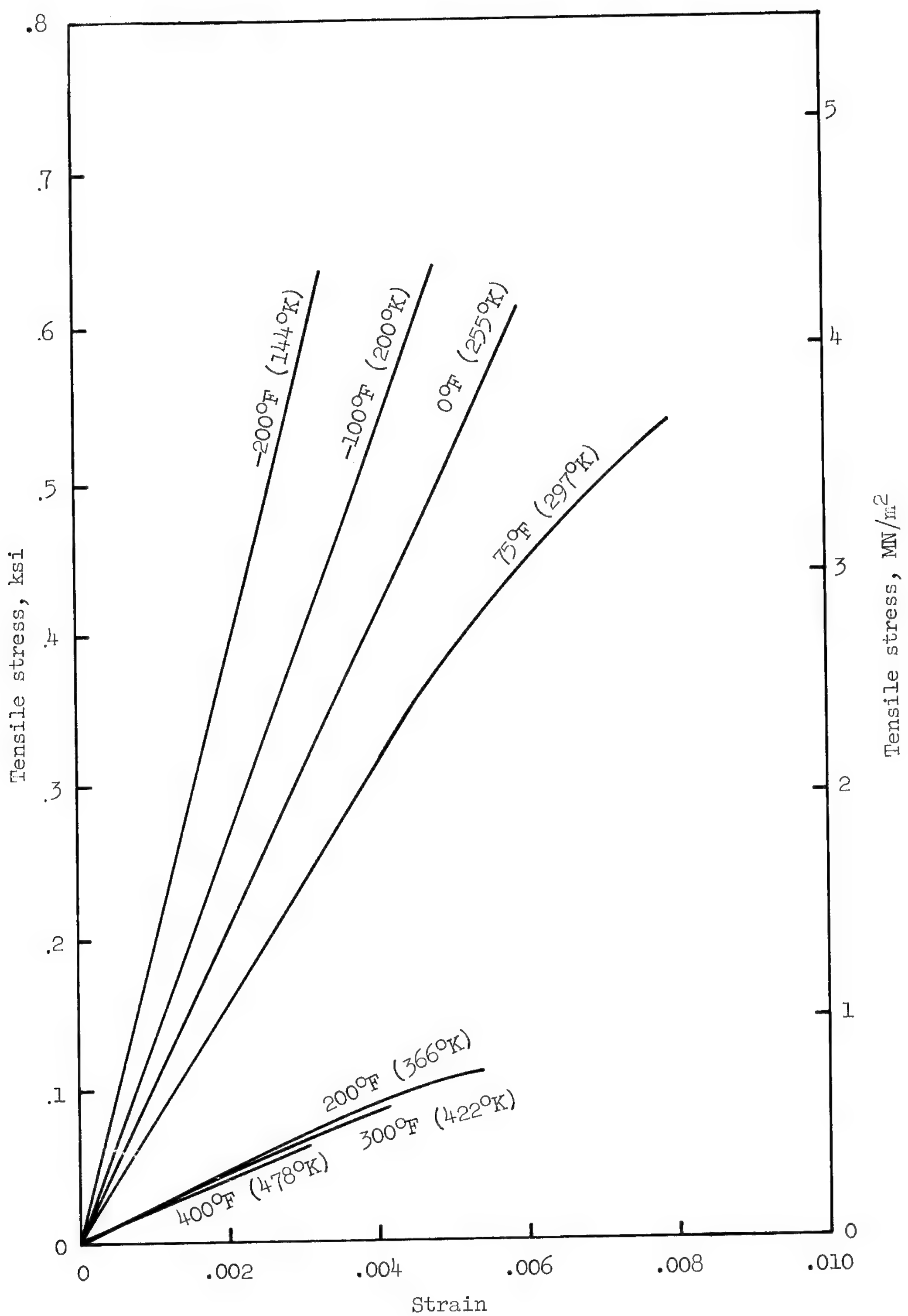


Figure 49.- Tensile stress-strain curves for Avcoat 5026-39-HC G filled epoxy in honeycomb (Melpar).

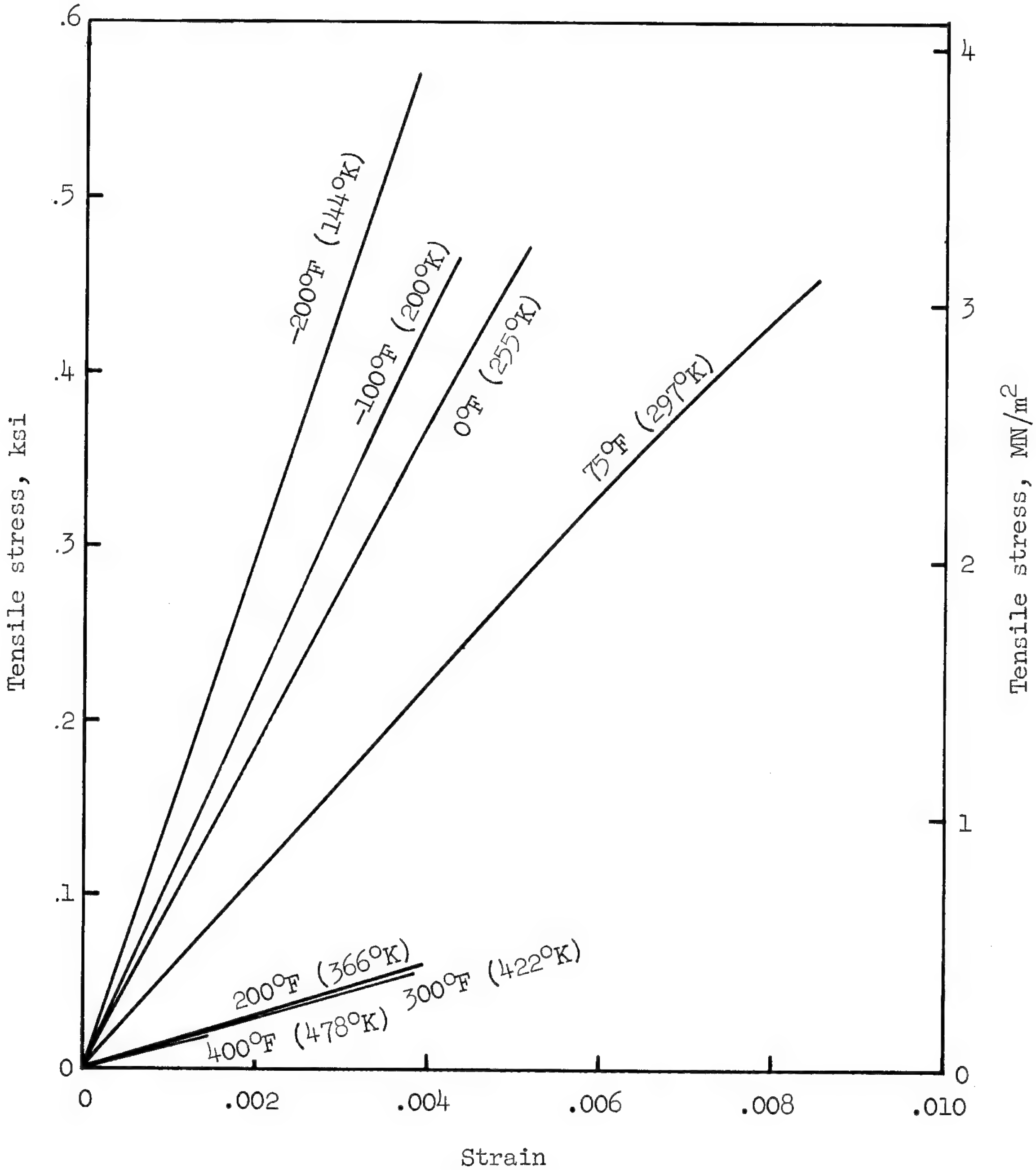


Figure 50.- Tensile stress-strain curves for Avcoat 5026-39-HC G filled epoxy in honeycomb in direction B (Melpar).

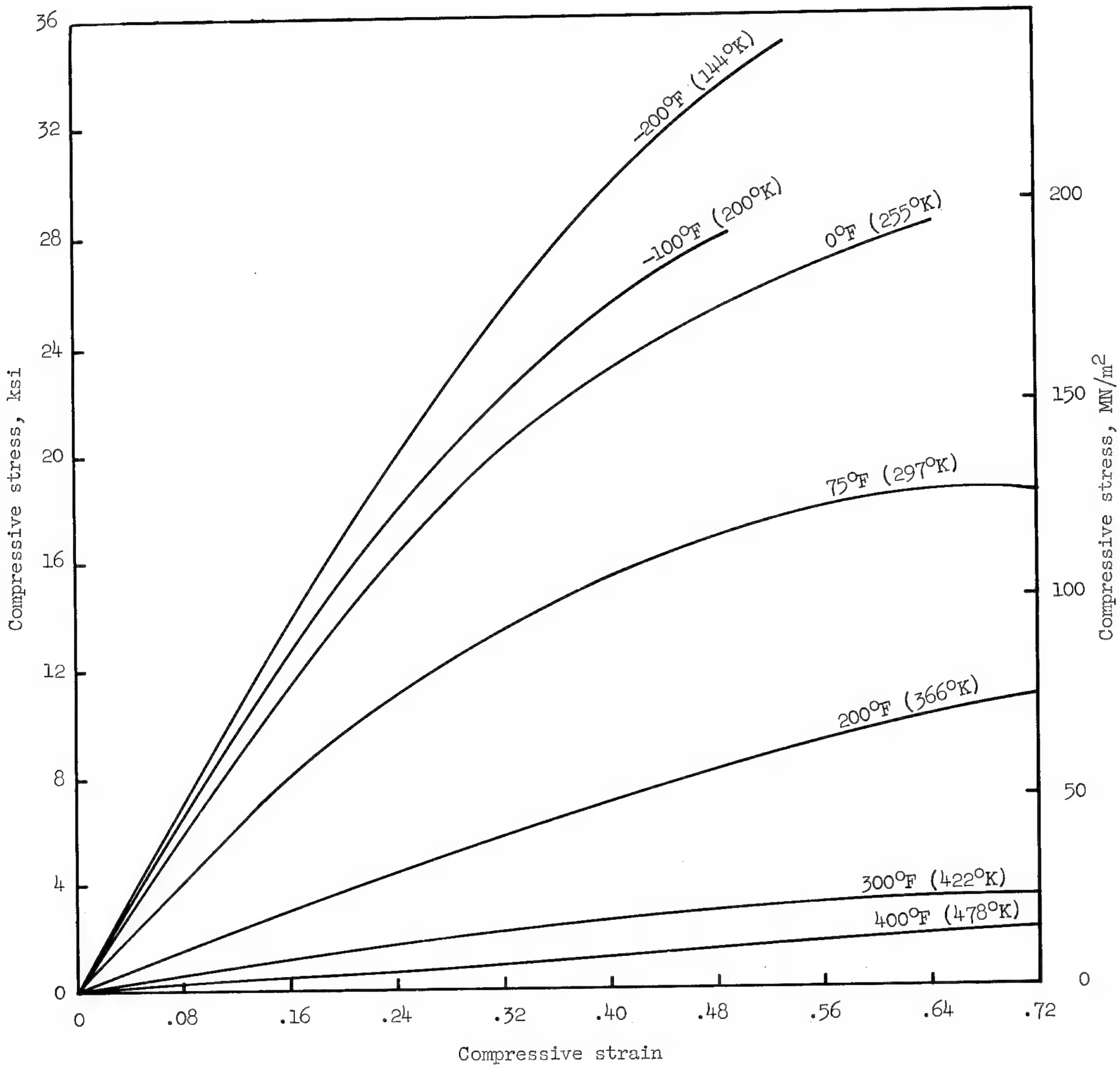


Figure 51.- Compressive stress-strain curves for high-density phenolic-nylon (Melpar).

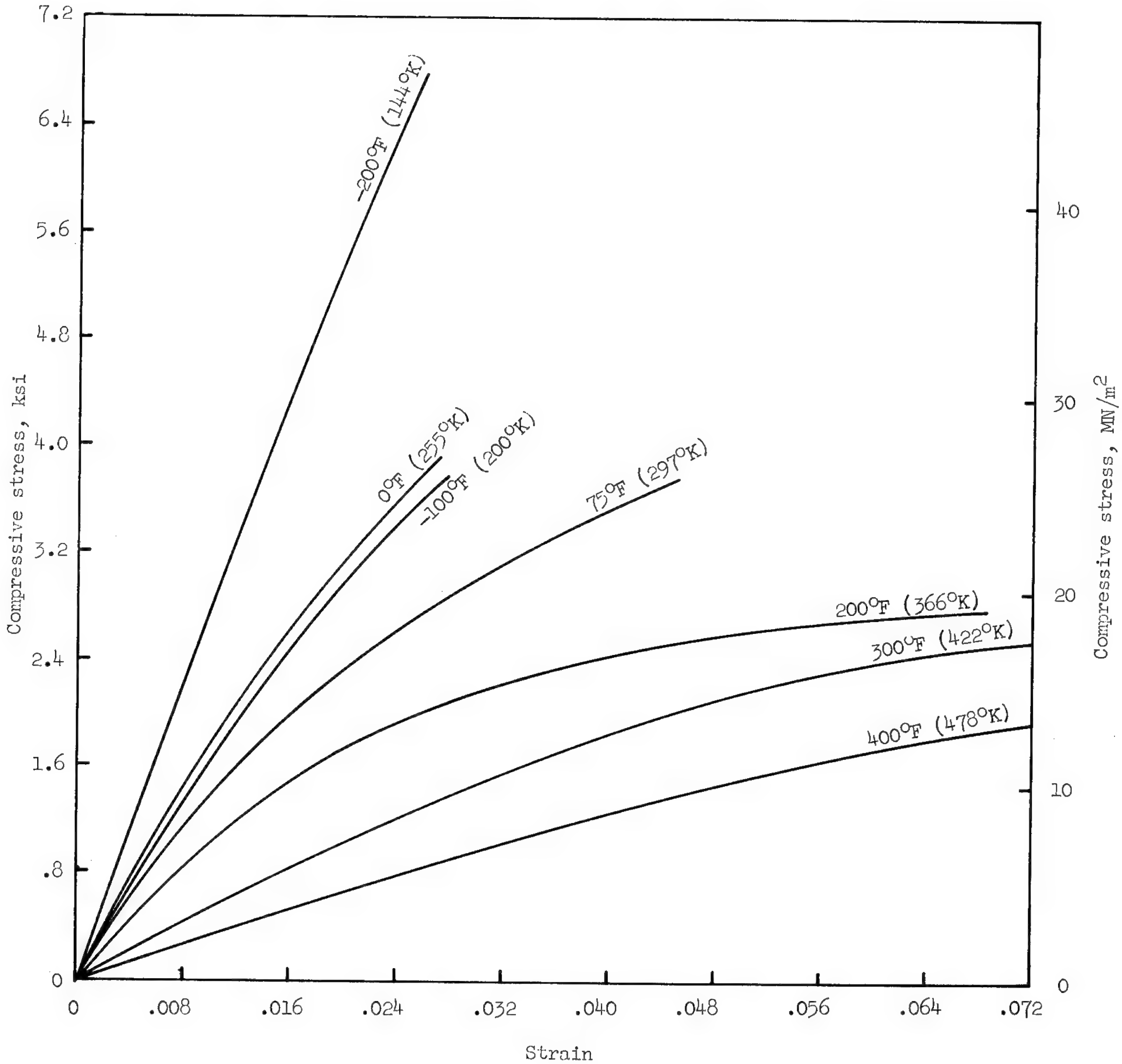


Figure 52.- Compressive stress of low-density phenolic-nylon (Melpar).

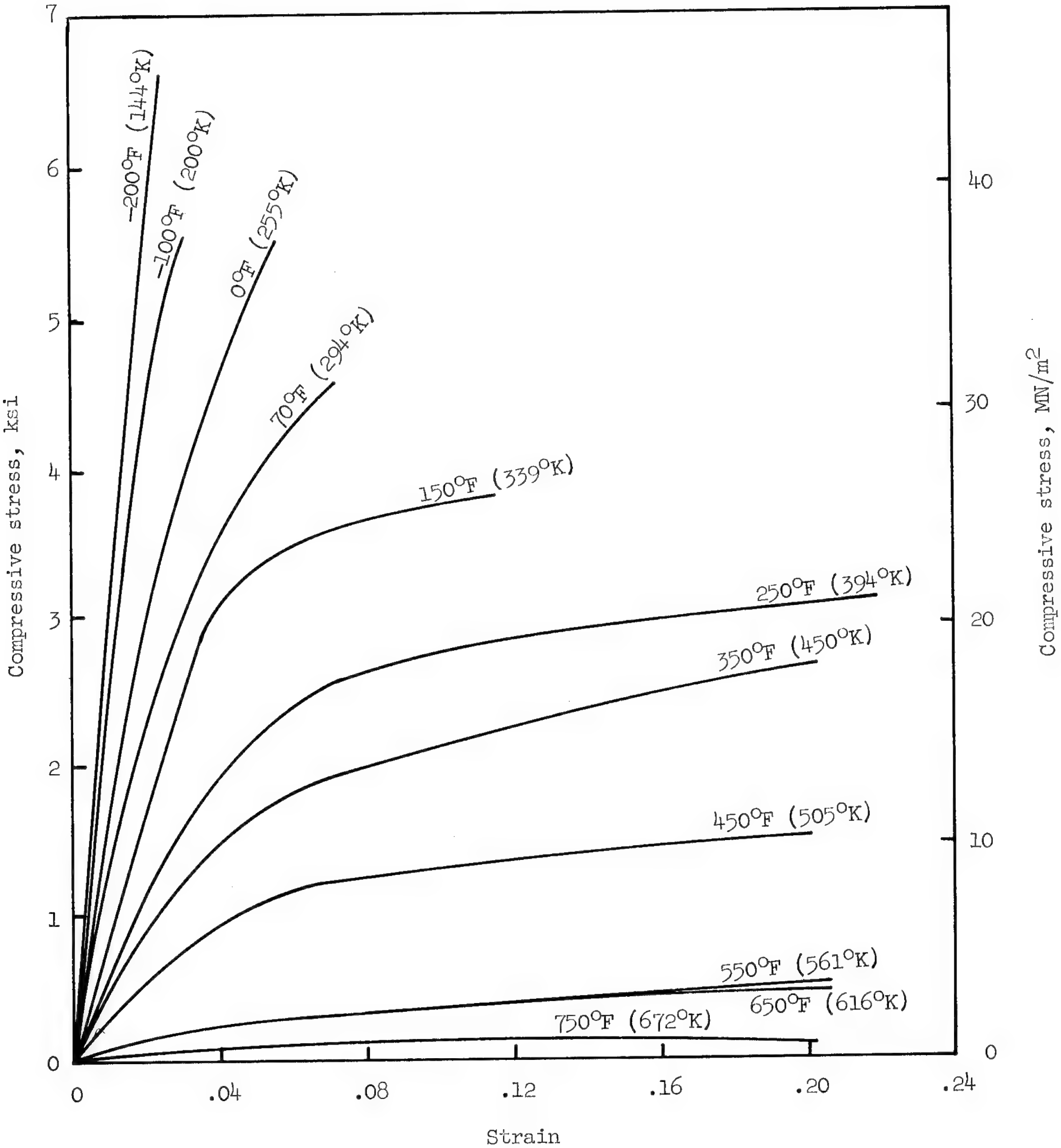


Figure 53.- Compressive stress-strain curves for low-density phenolic-nylon (SRI).

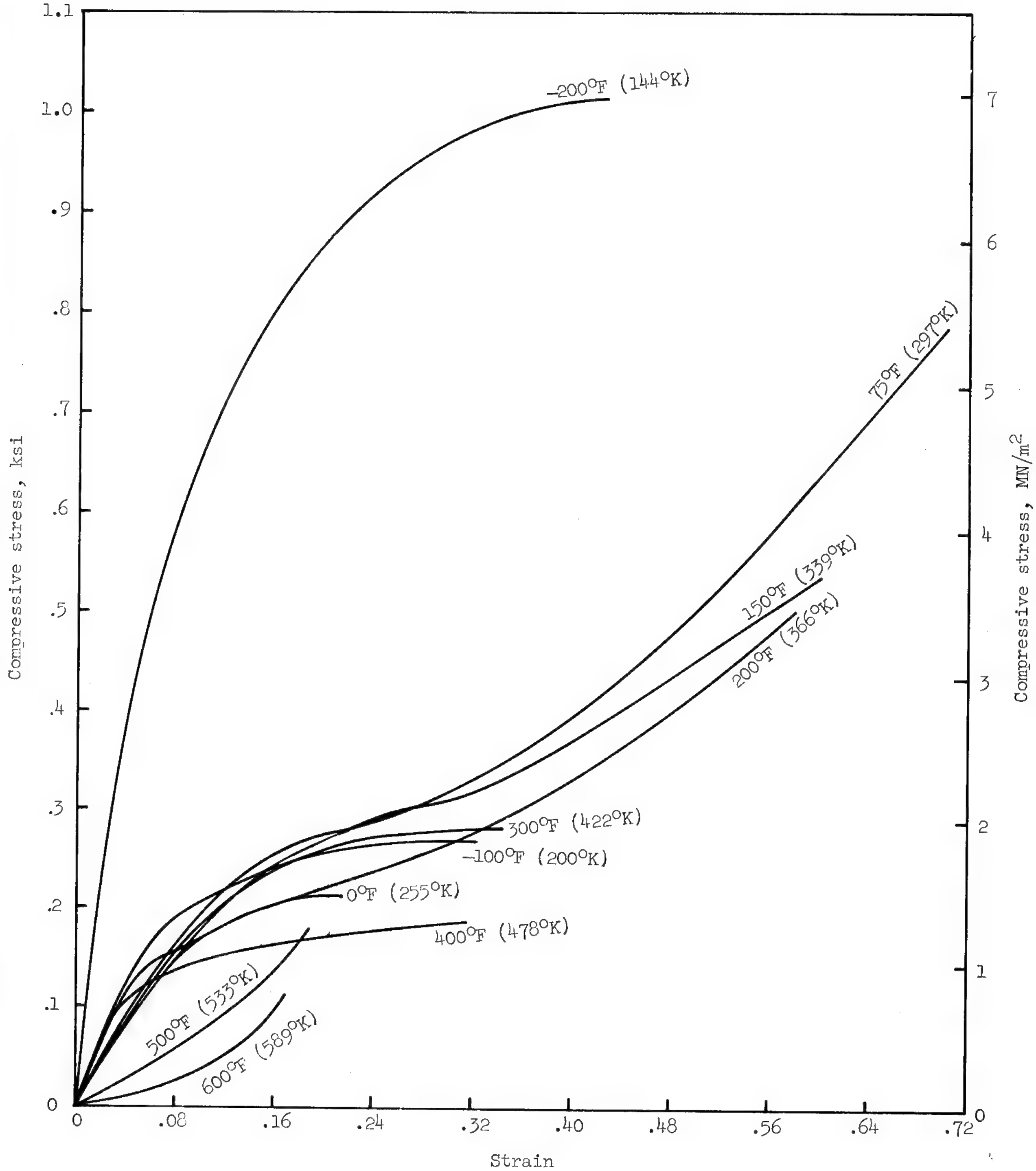


Figure 54.- Compressive stress-strain curves for filled silicone resin (Melpar).

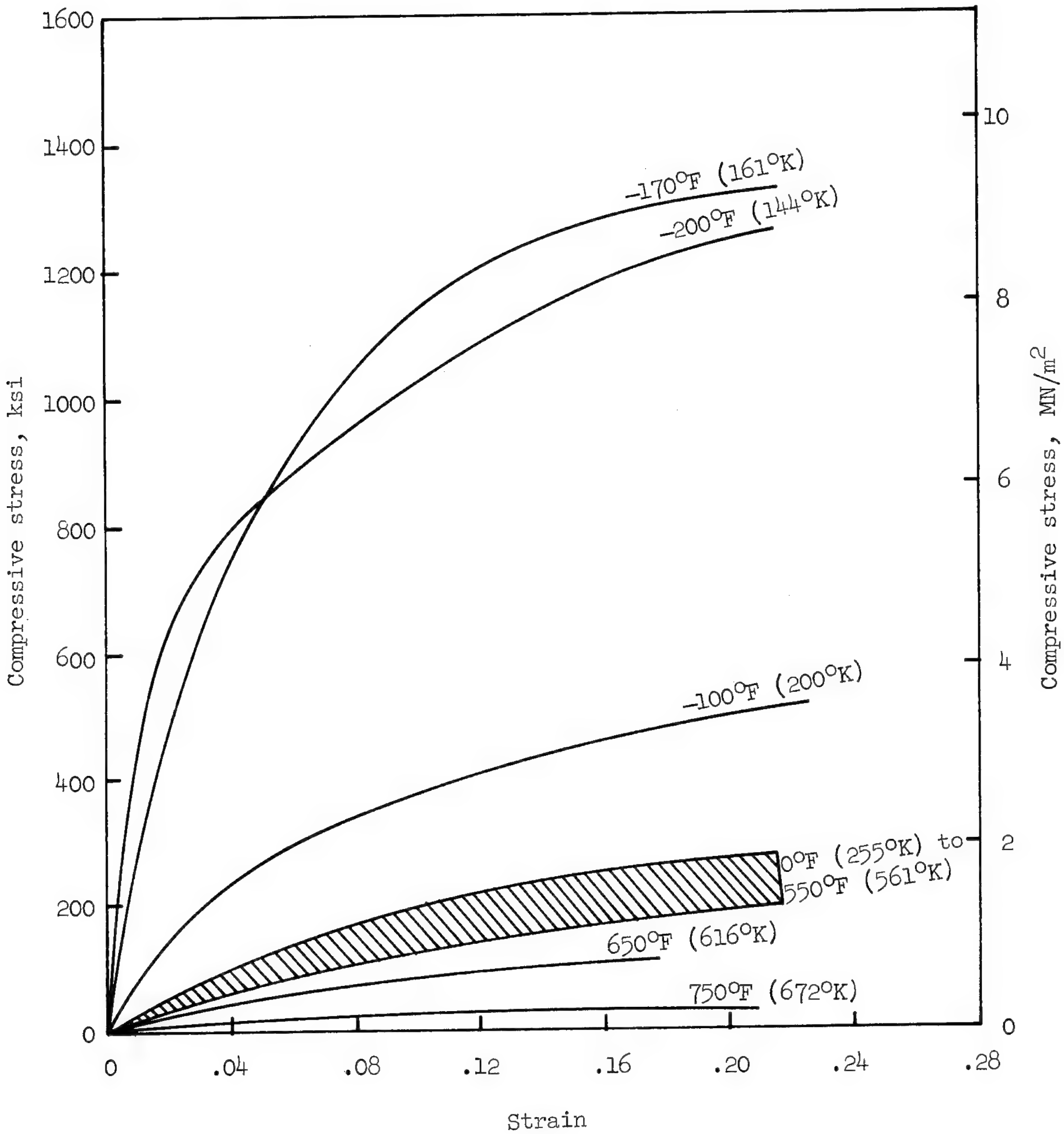


Figure 55.- Compressive stress-strain curves for filled silicone resin (SRI).

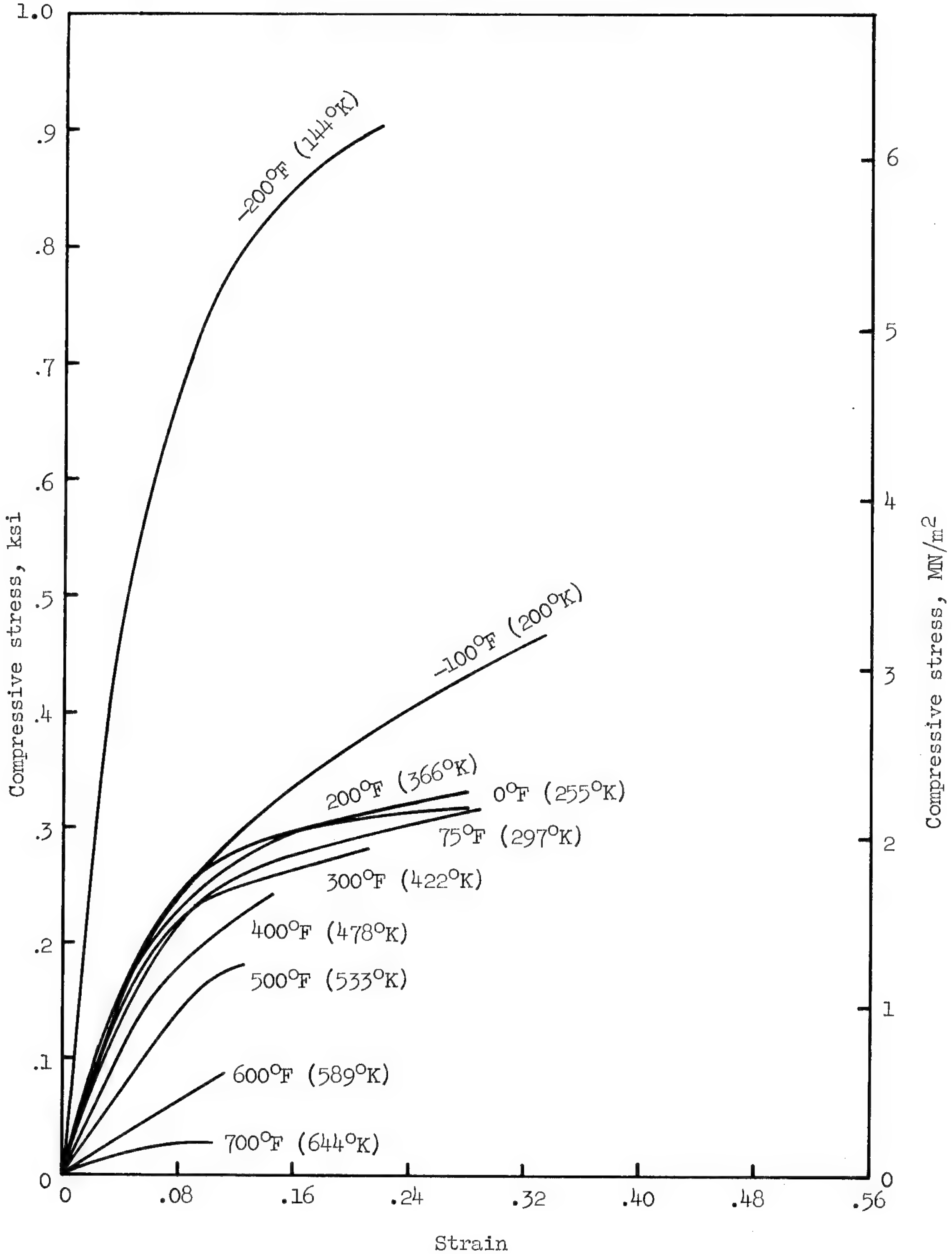


Figure 56.- Compressive stress-strain curves for direction A of filled silicone resin in honeycomb (Melpar).

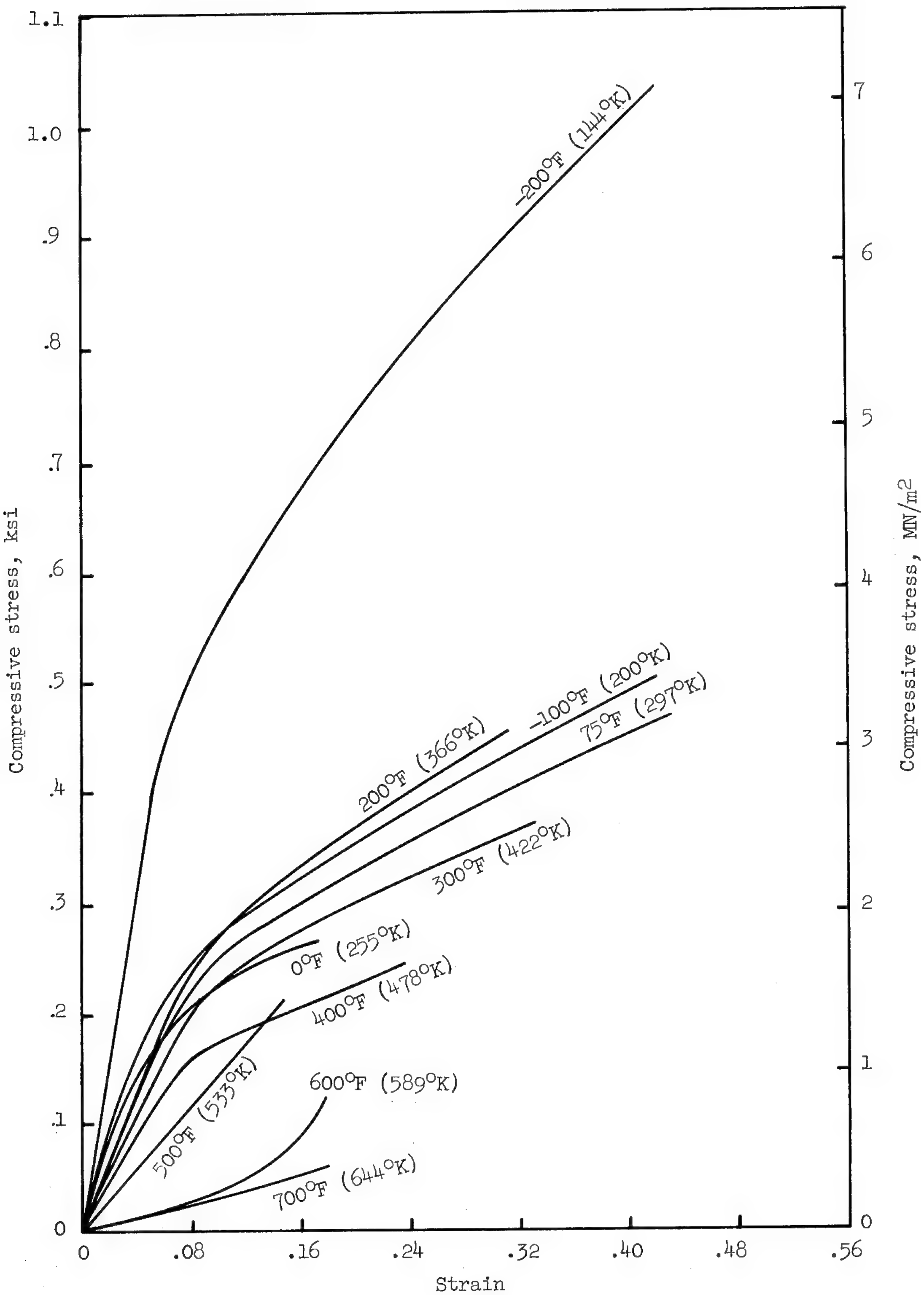


Figure 57.- Compressive stress-strain curves for direction B of filled silicone resin in honeycomb (Melpar).

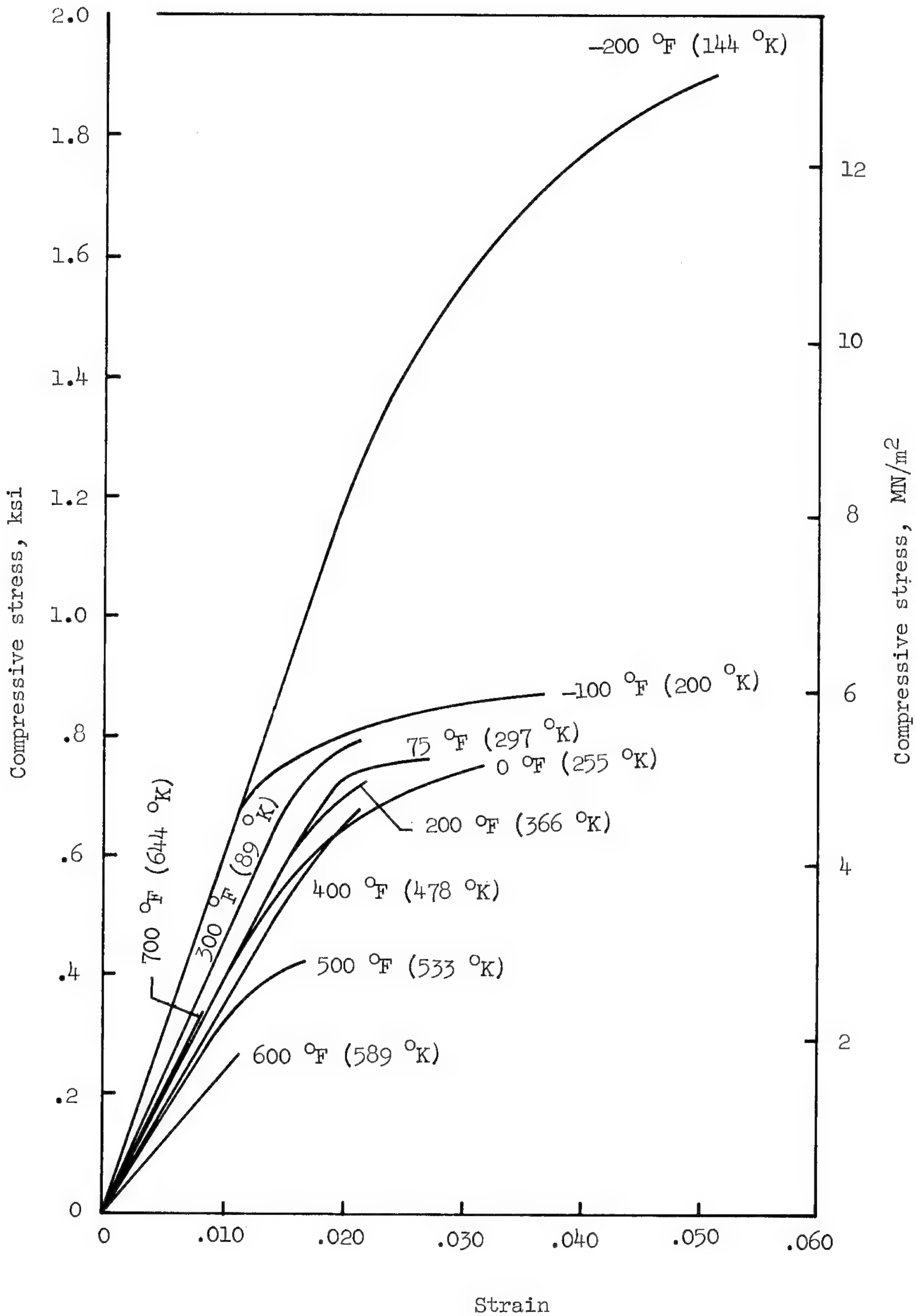


Figure 58.- Compressive stress-strain curves for direction C of filled silicone resin in honeycomb (Melpar).

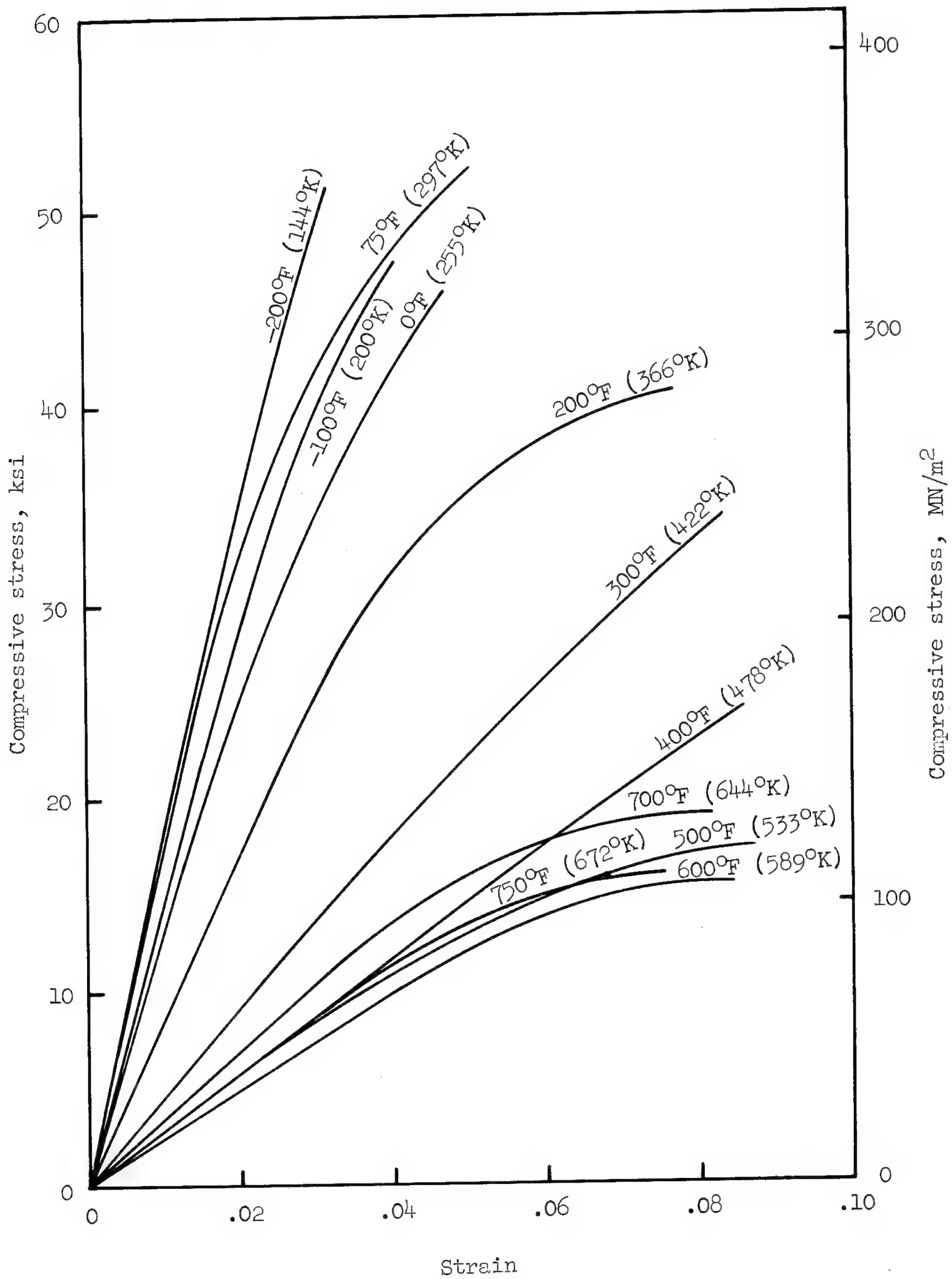


Figure 59.- Compressive stress-strain curves for Narmco 4028 carbon-fiber-reinforced phenolic (Melpar).

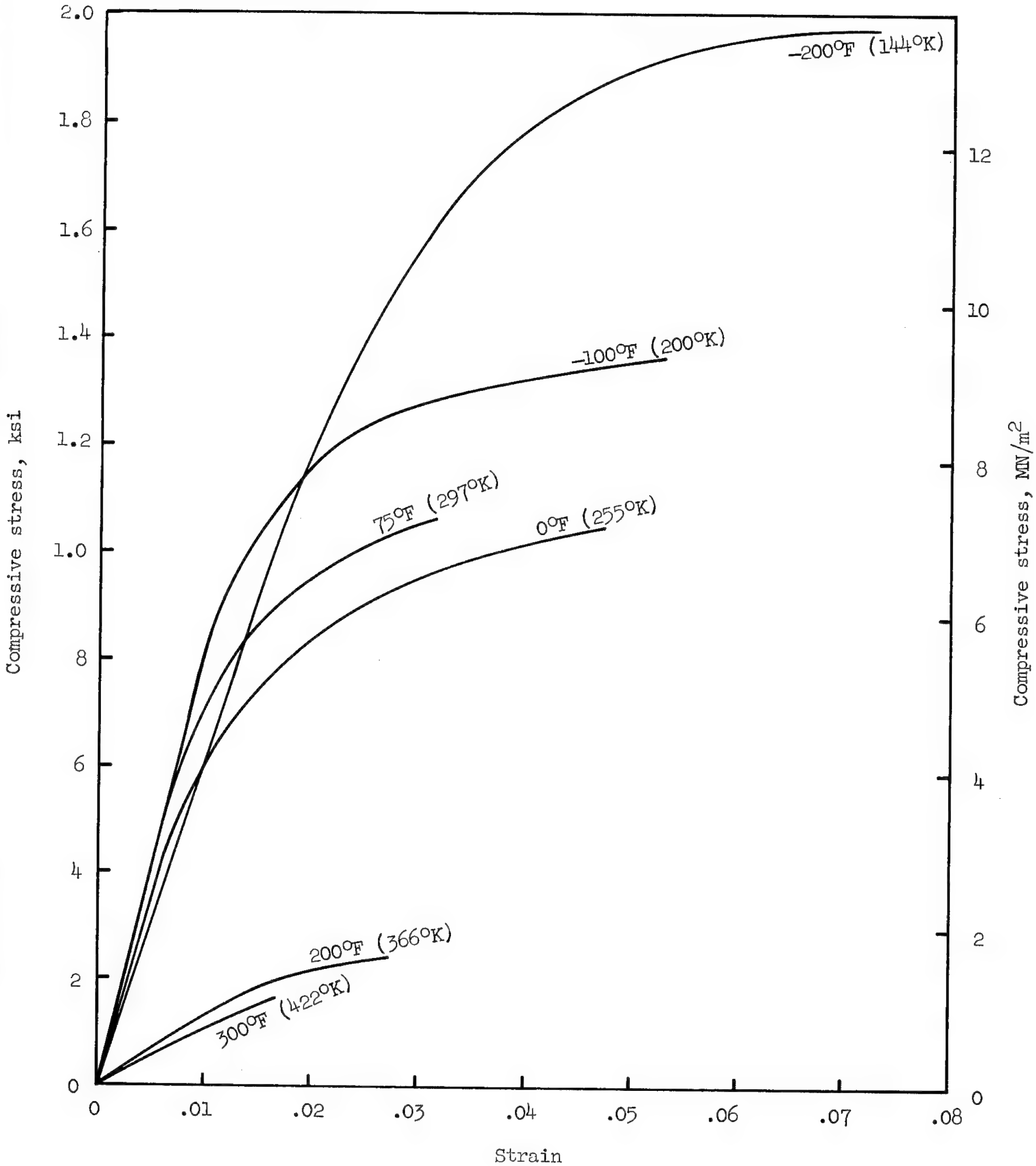


Figure 60.- Compressive stress-strain curves for Avcoat 5026-39-HC G filled epoxy in honeycomb in direction A (Melpar).

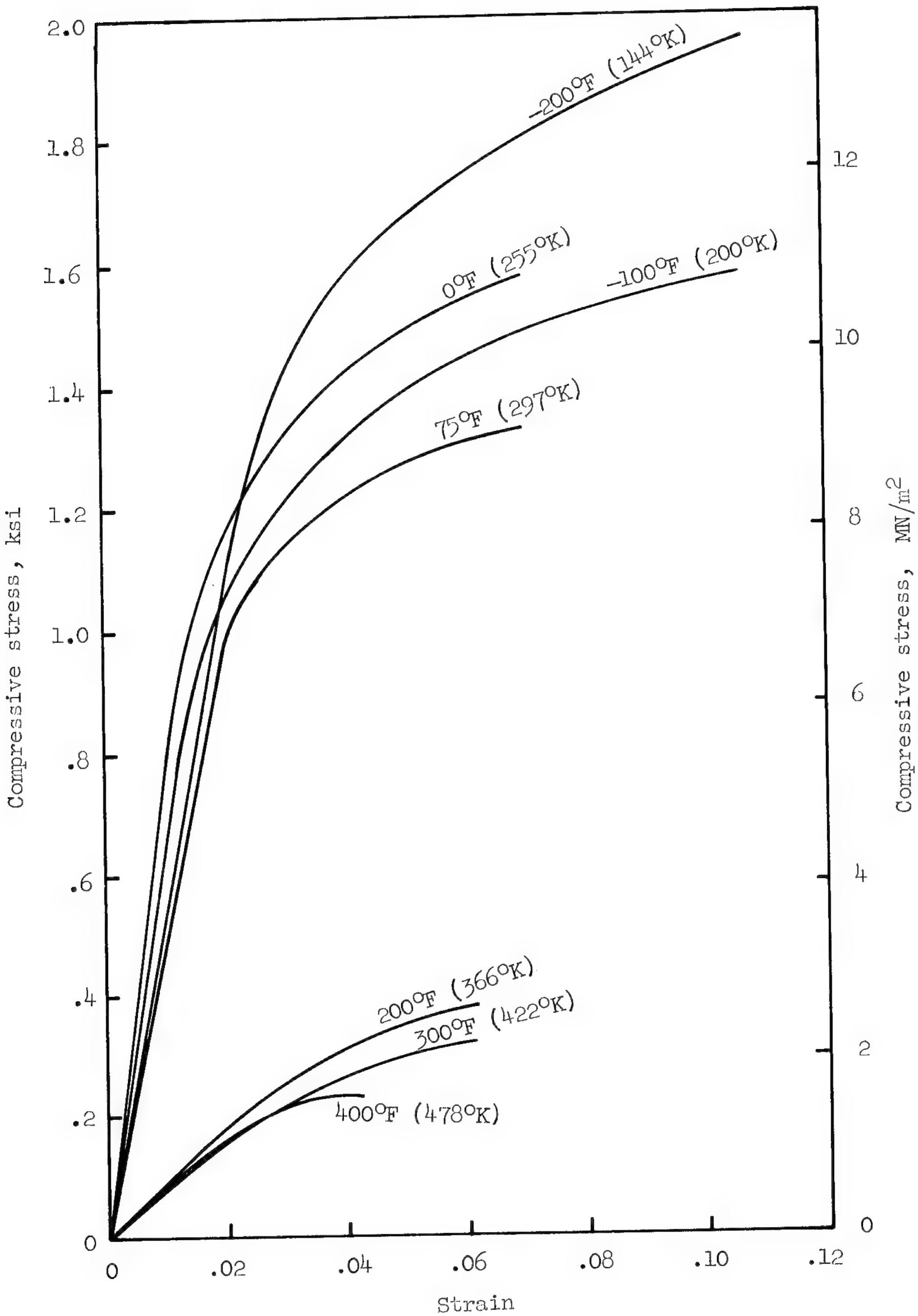


Figure 61.- Compressive stress-strain curves for Avcoat 5026-39-HC G filled epoxy in honeycomb in direction B (Melpar).

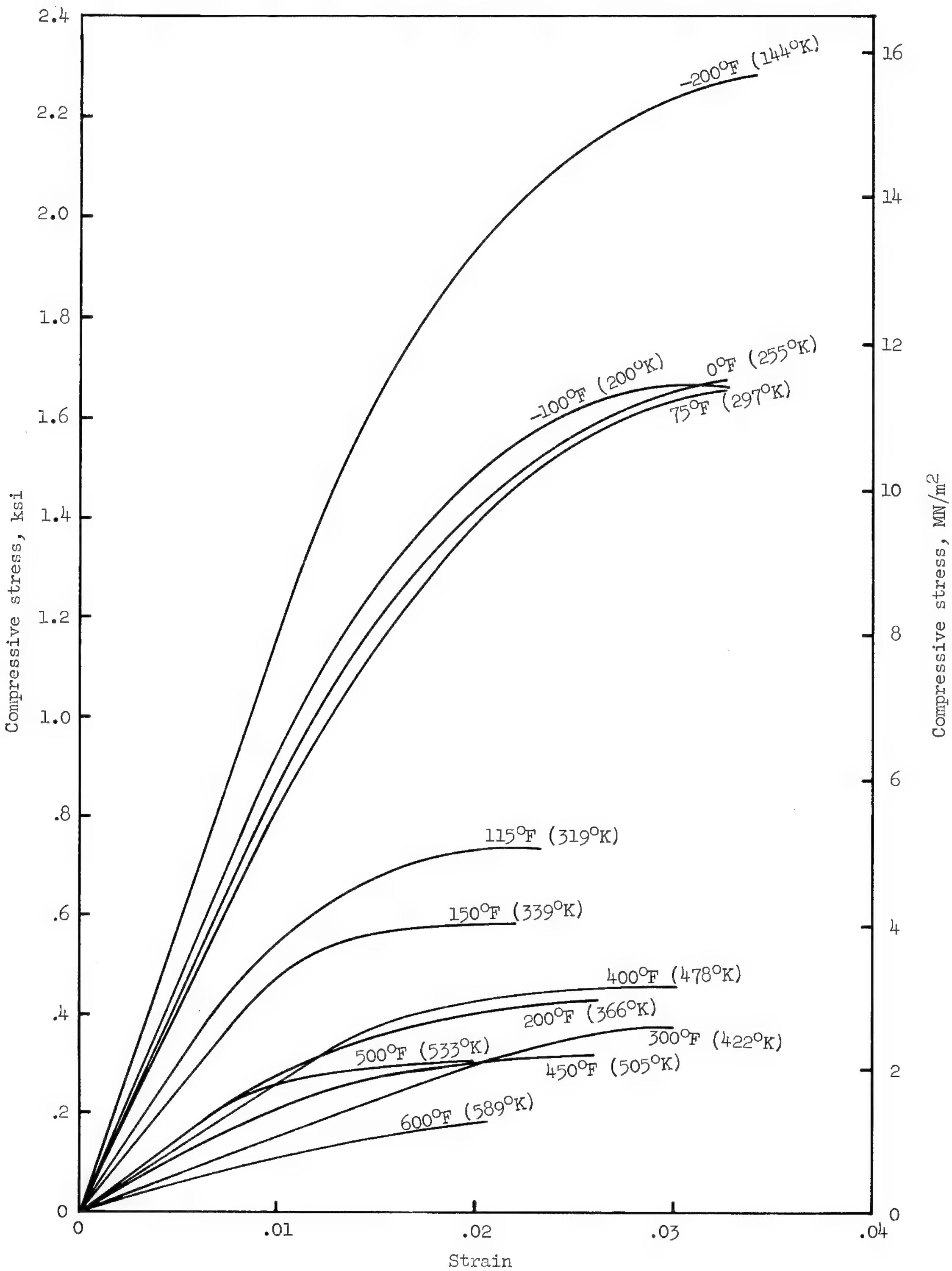


Figure 62.- Compressive stress-strain curves for Avcoat 5026-39-HC G filled epoxy in honeycomb in direction C (Melpar).

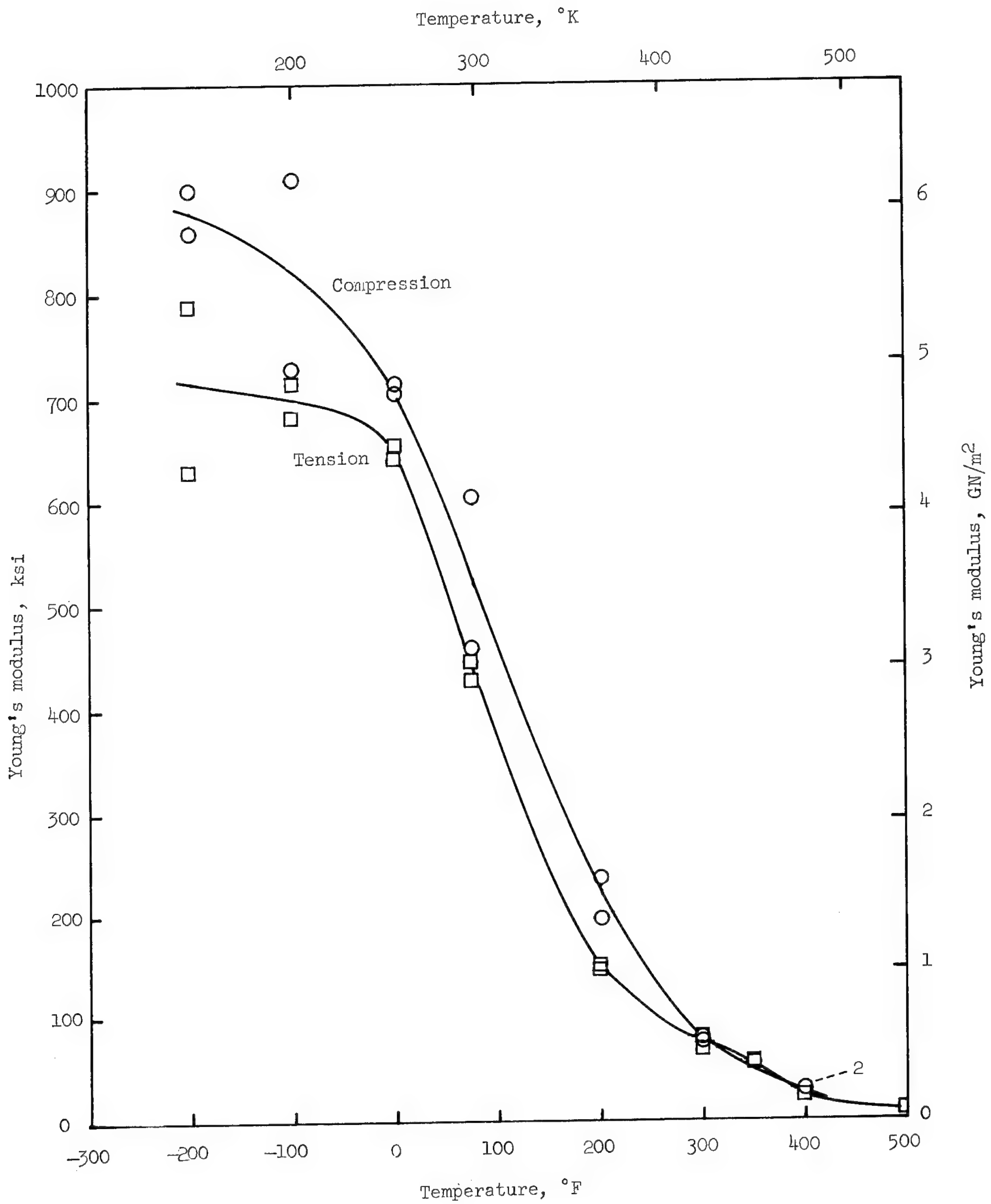


Figure 63.- Young's modulus of high-density phenolic-nylon in tension and compression (Melpar).

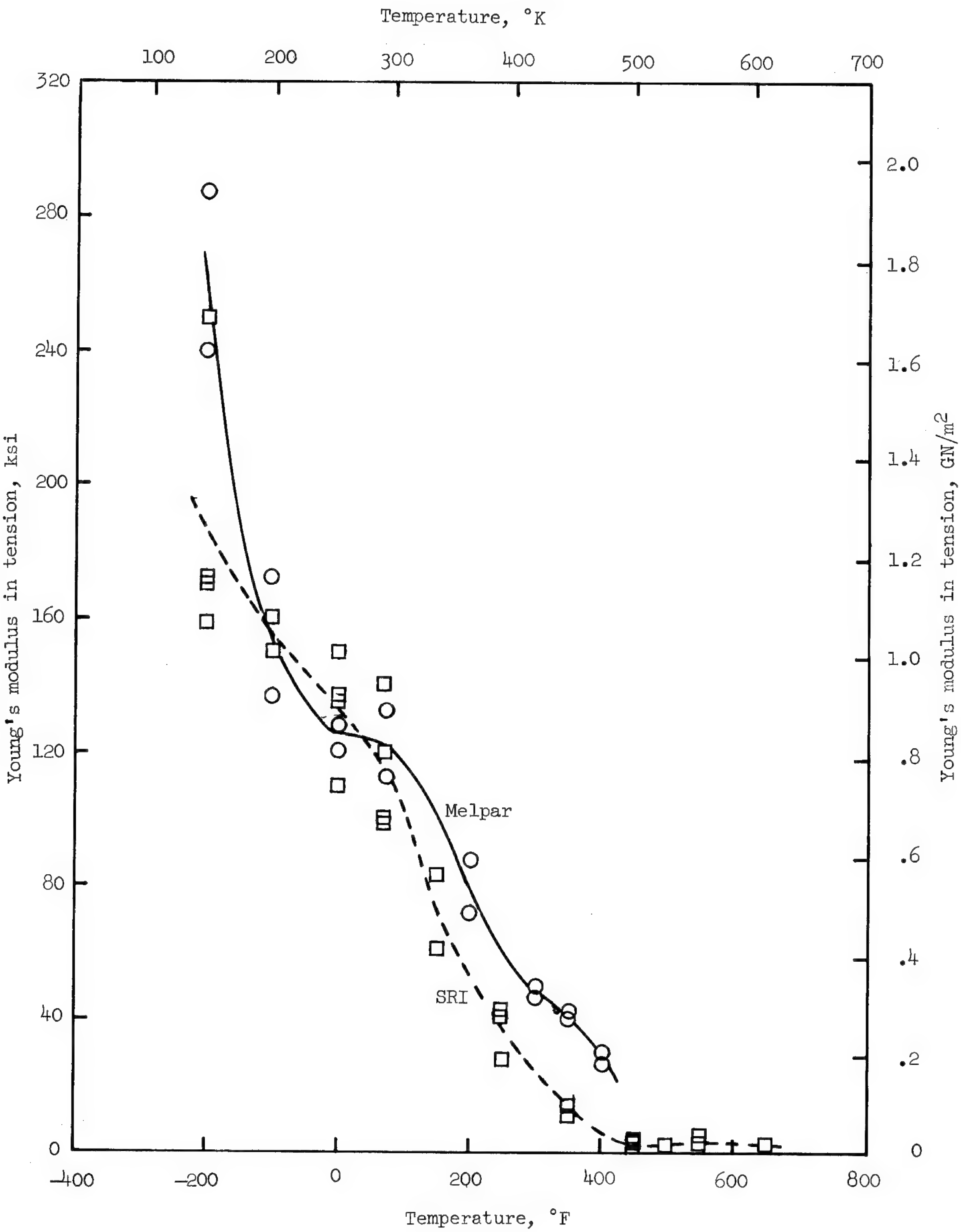


Figure 64.- Young's modulus in tension for low-density phenolic-nylon.

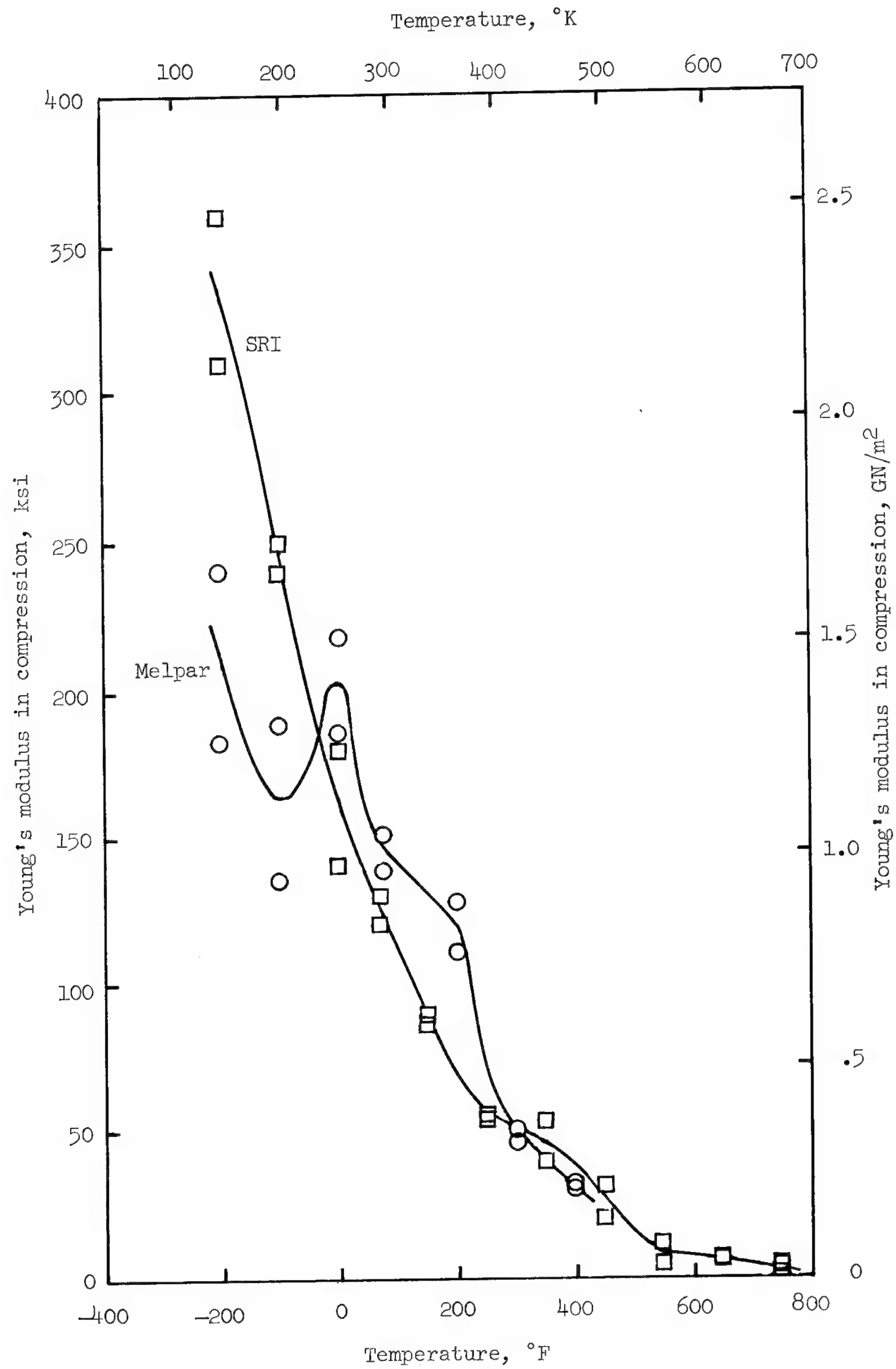


Figure 65.- Young's modulus of low-density phenolic-nylon in compression.

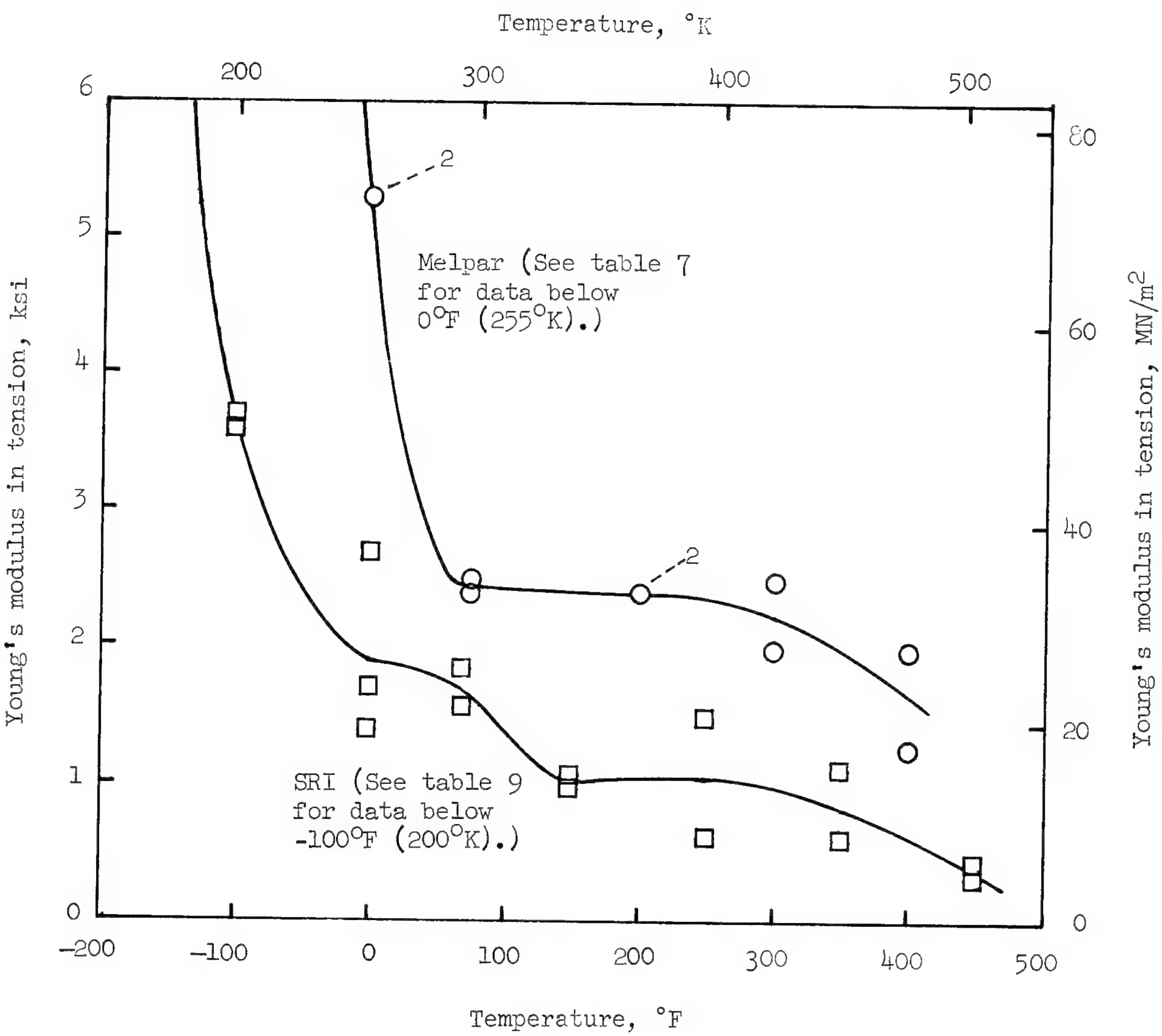


Figure 66.- Young's modulus of filled silicone resin in tension.

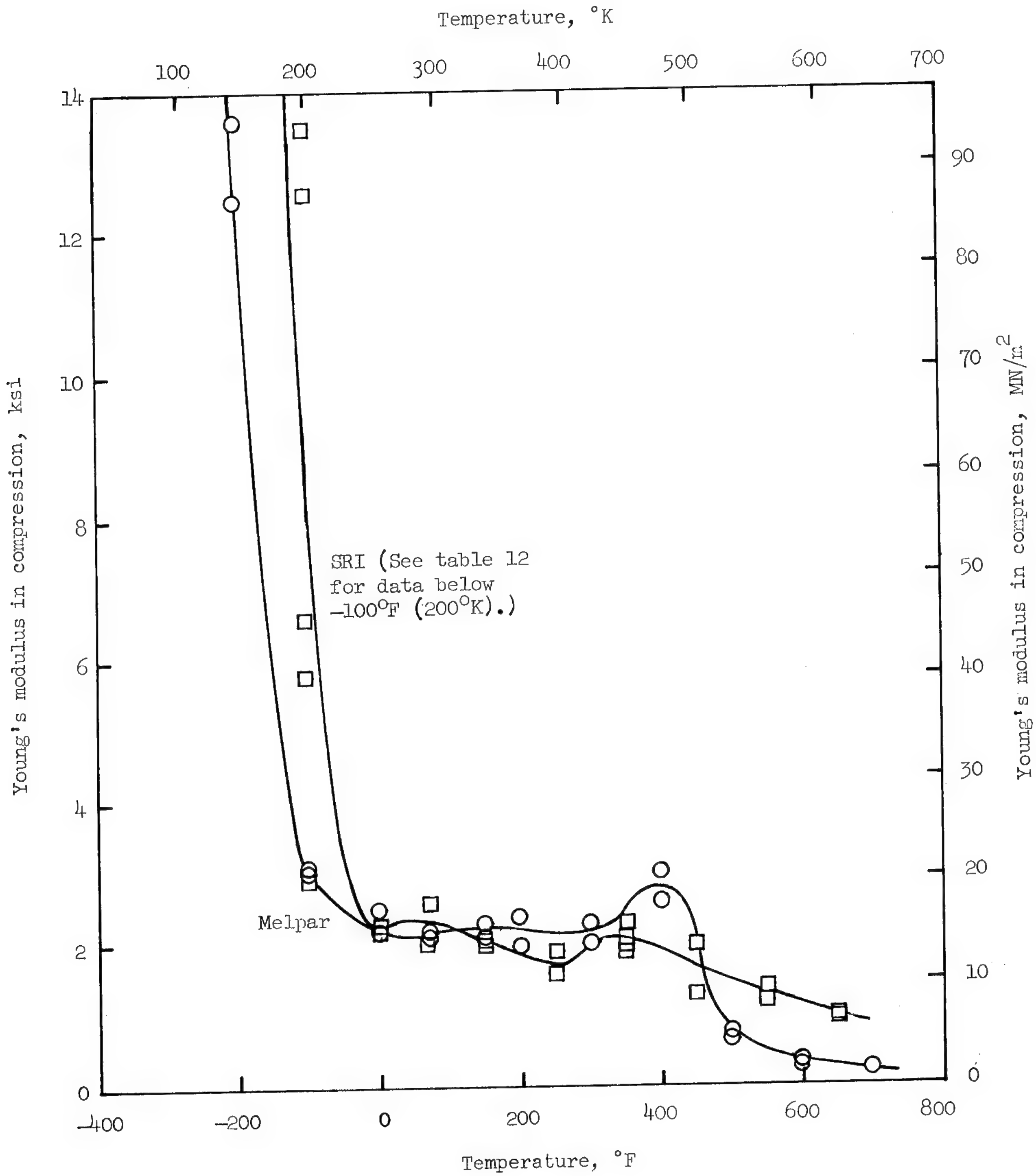


Figure 67.- Young's modulus of filled silicone resin in compression.

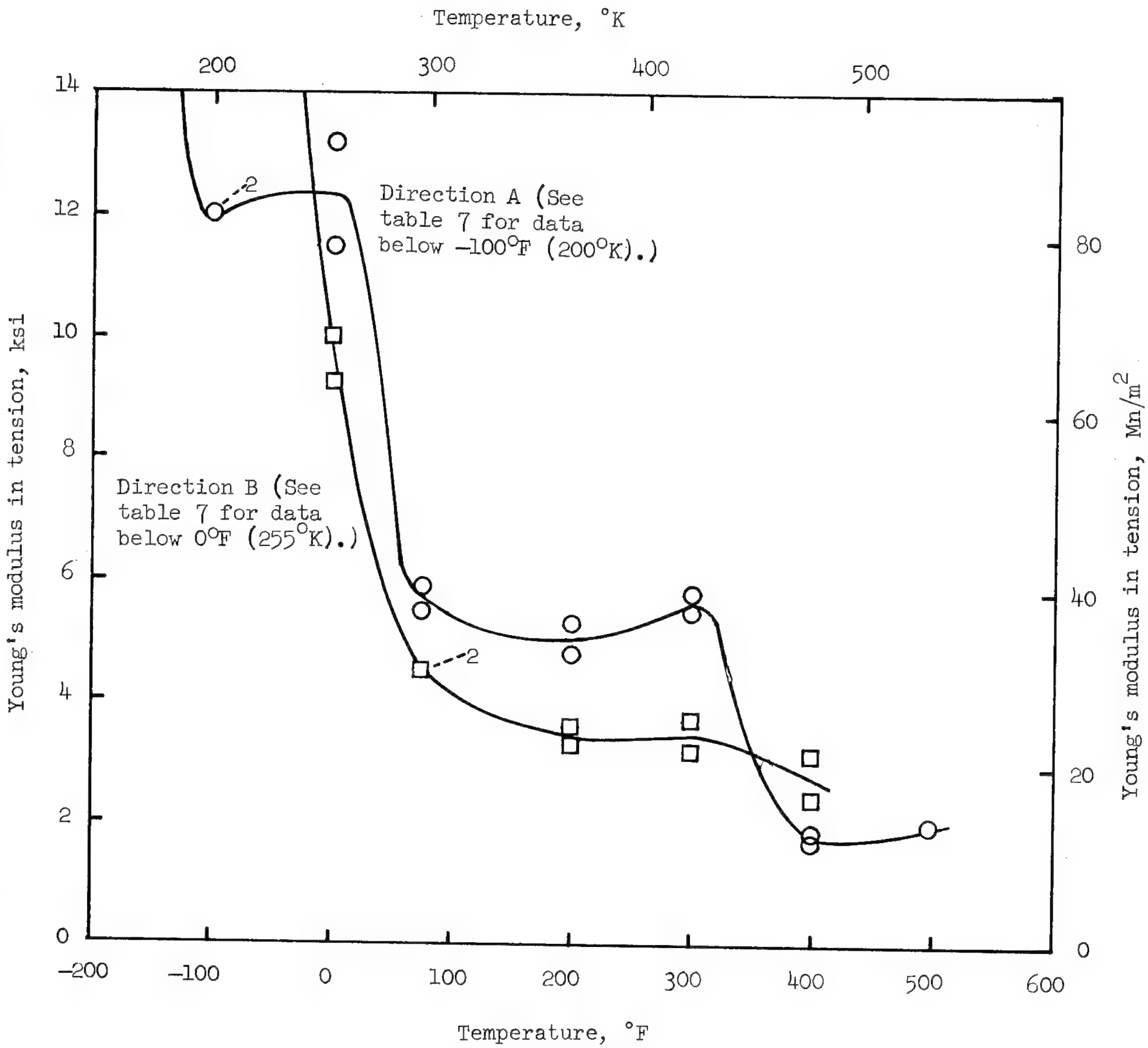


Figure 68.- Young's modulus in tension for filled silicone resin in honeycomb (Melpar).

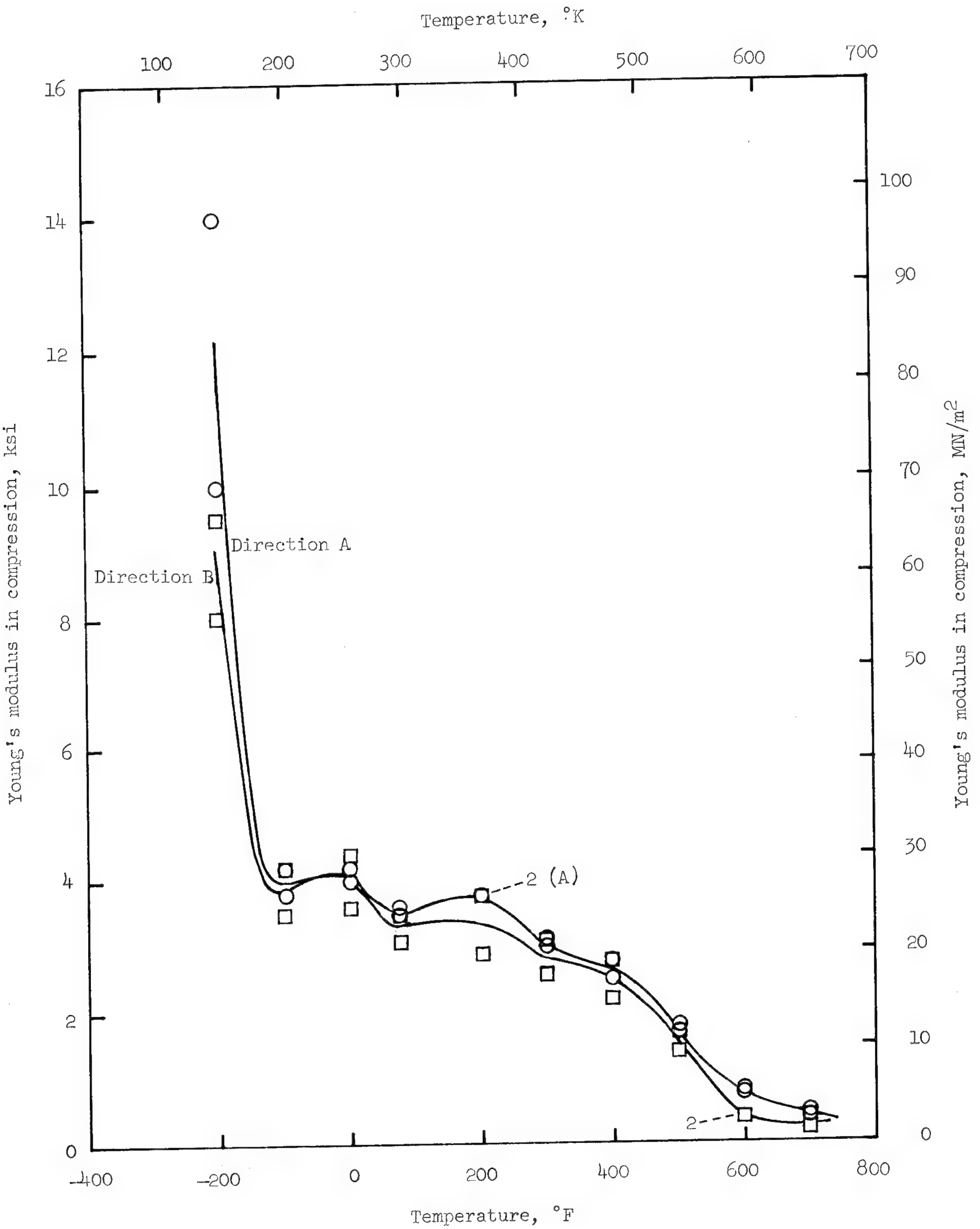


Figure 69.- Young's modulus in directions A and B for filled silicone resin in honeycomb in compression (Melpar).

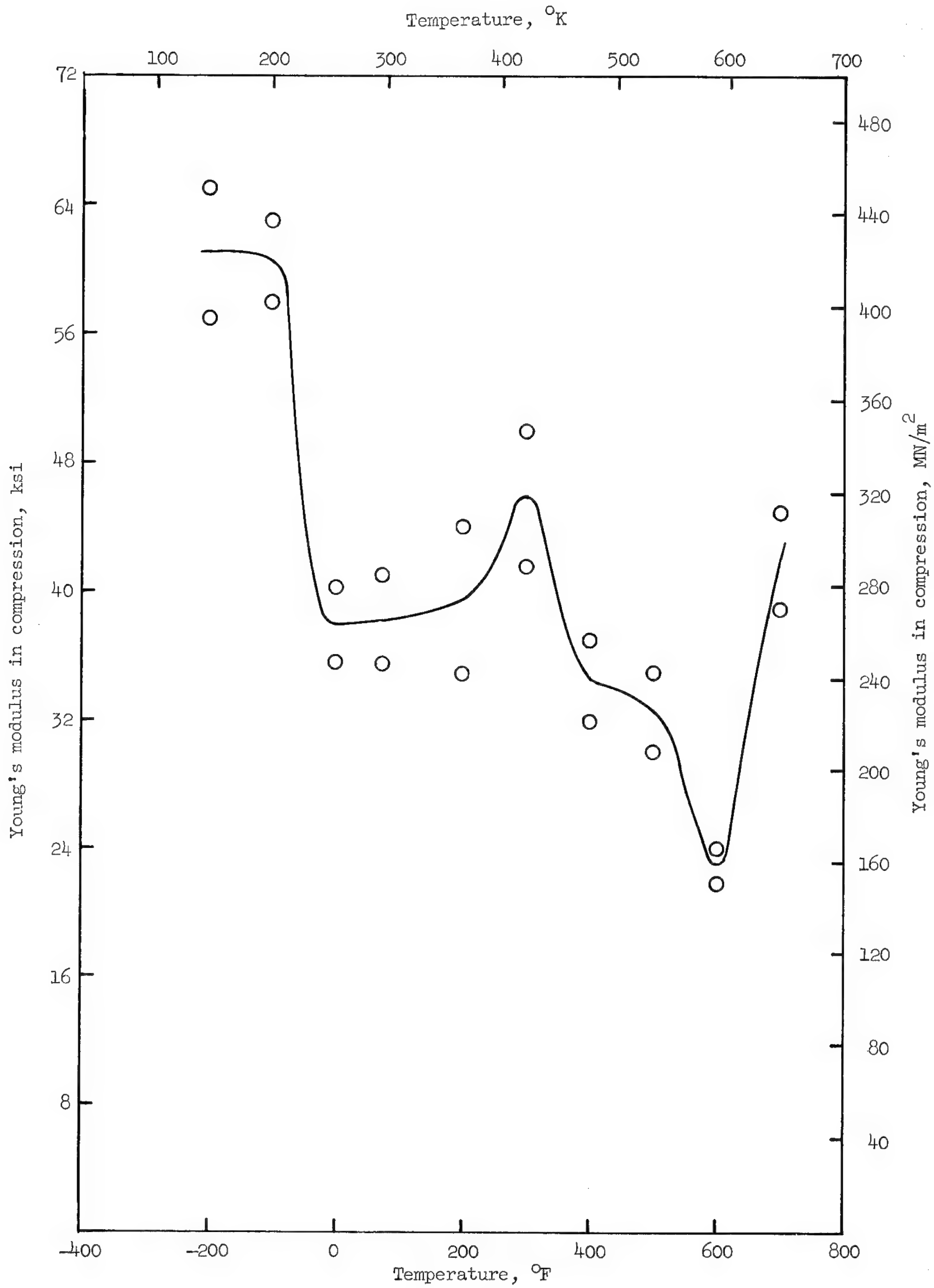


Figure 70.- Young's modulus in direction C for filled silicone resin in honeycomb (Melpar).

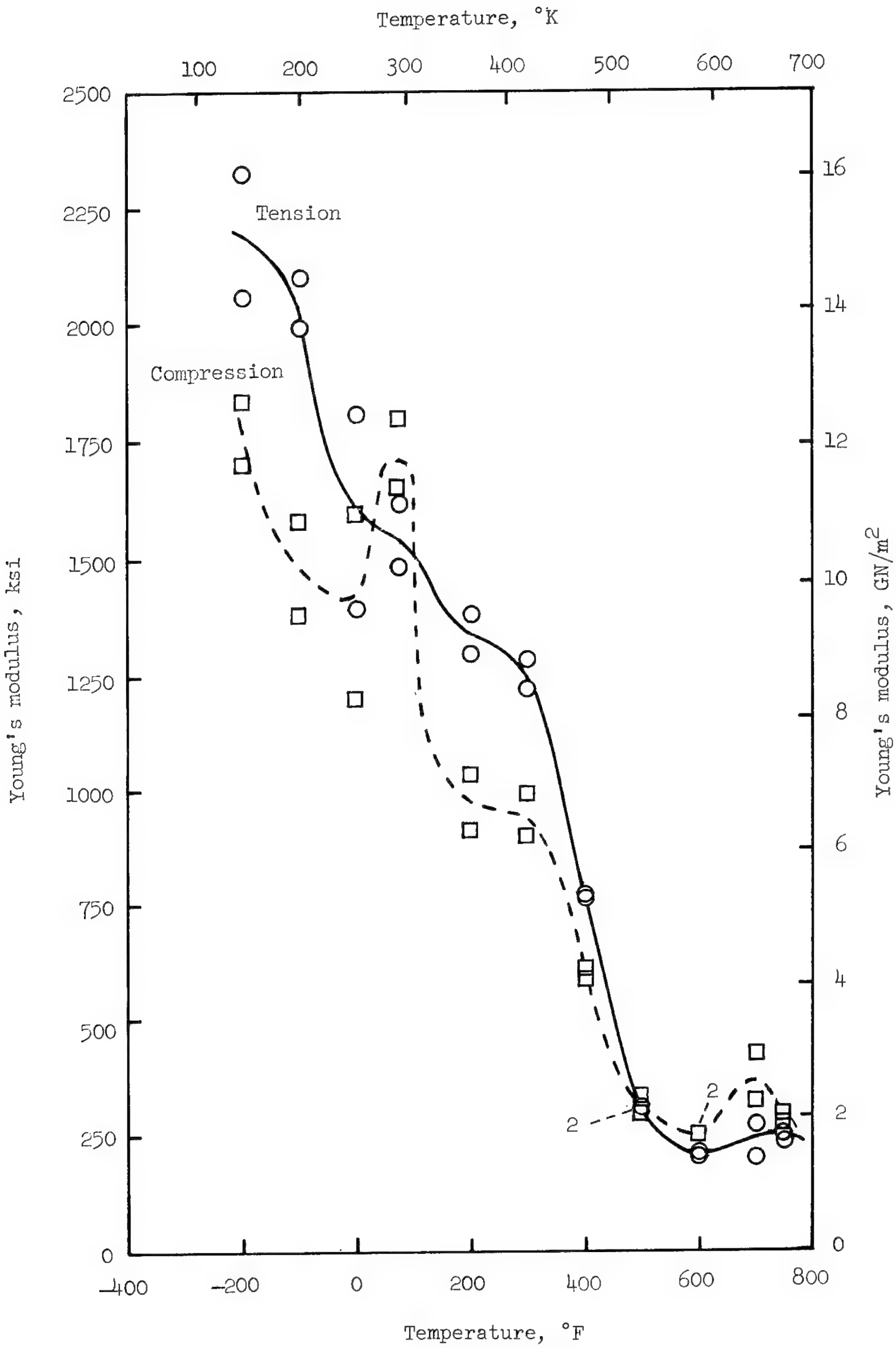


Figure 71.- Young's modulus of Narmco 4028 carbon-fiber-reinforced phenolic in tension and compression (Melpar).

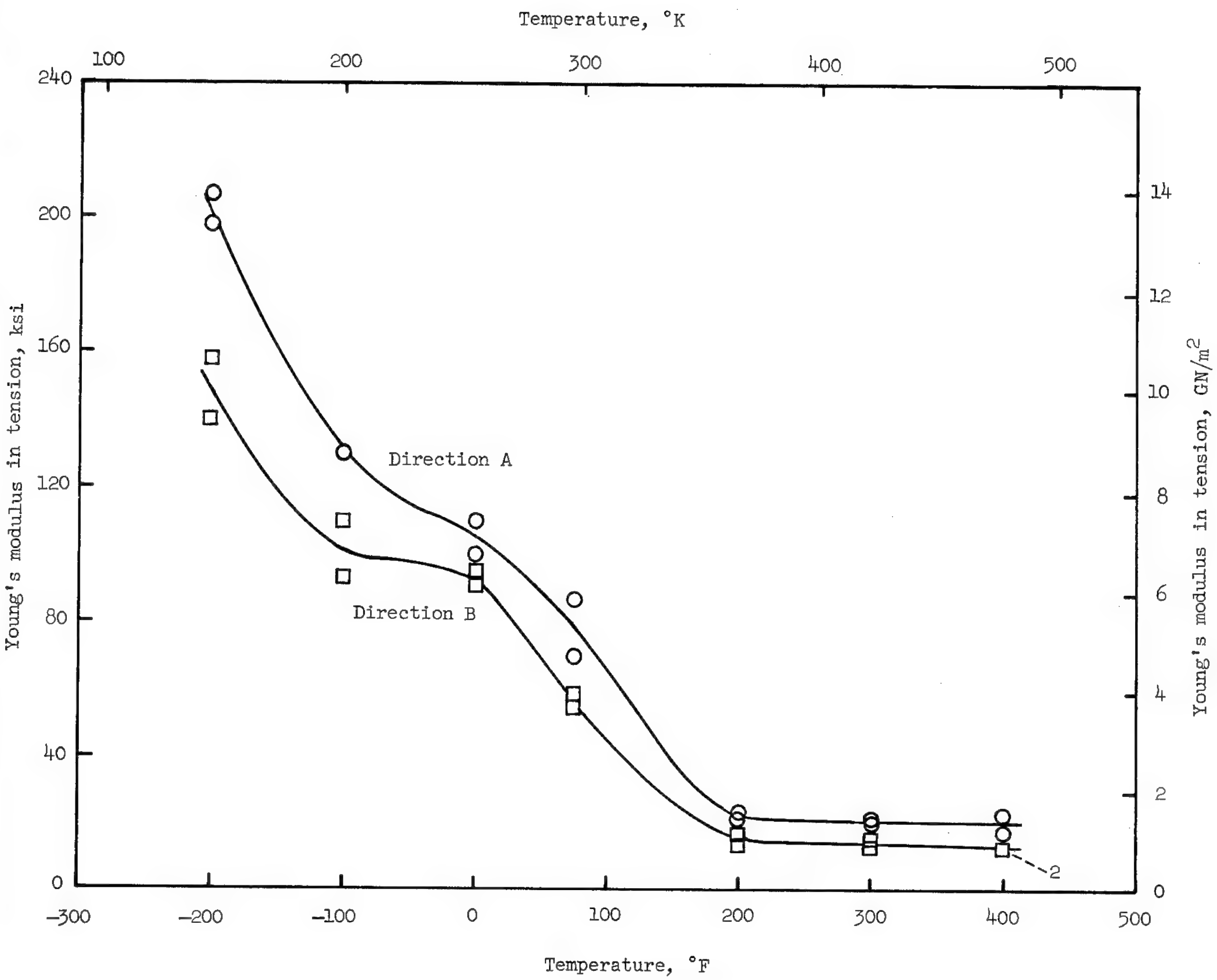


Figure 72.- Young's modulus of Avcoat 5026-39-HC G filled epoxy in honeycomb in tension (Melpar).

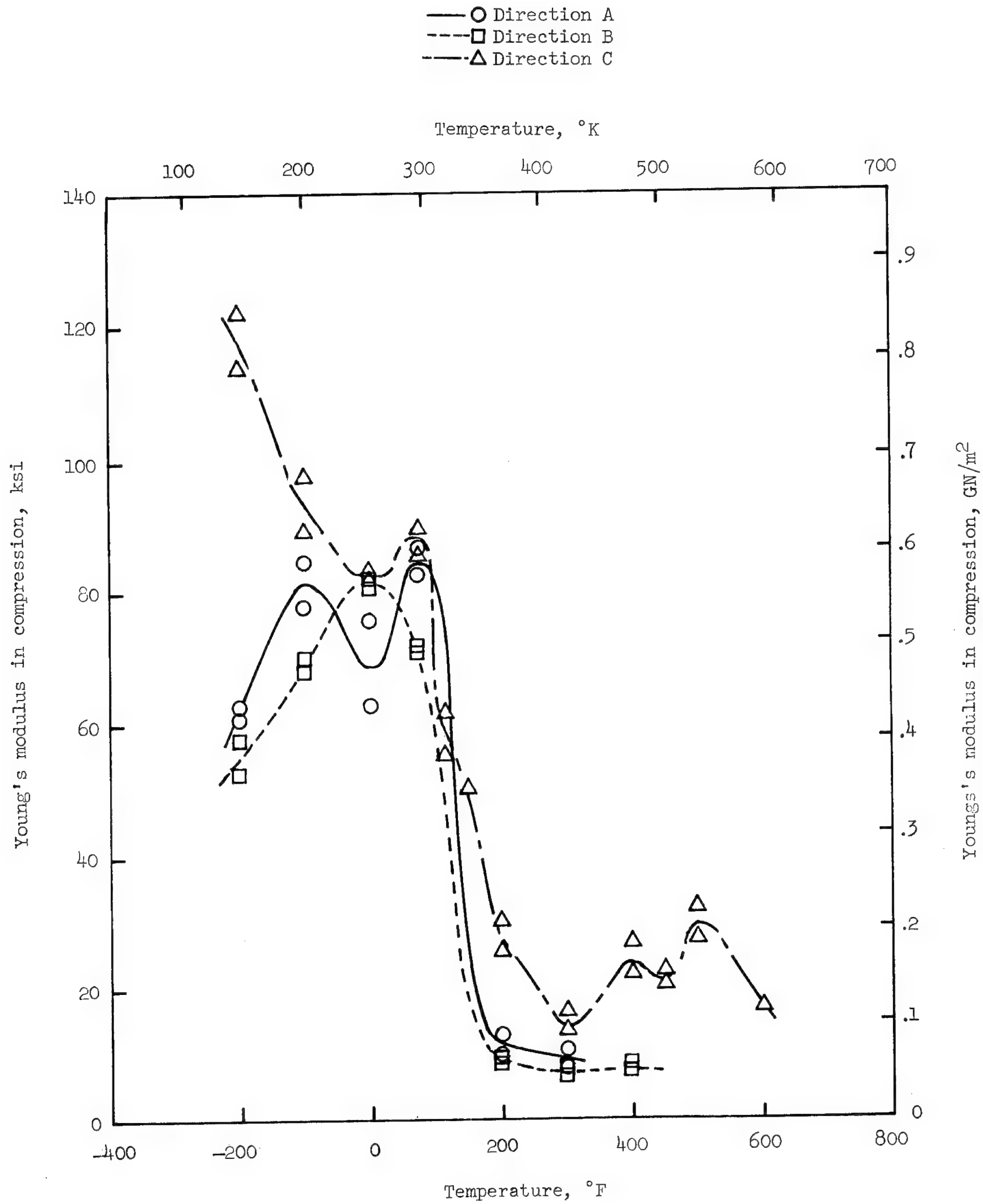


Figure 73.- Young's modulus of Avcoat 5026-39-HC G filled epoxy in honeycomb in compression (Melpar).

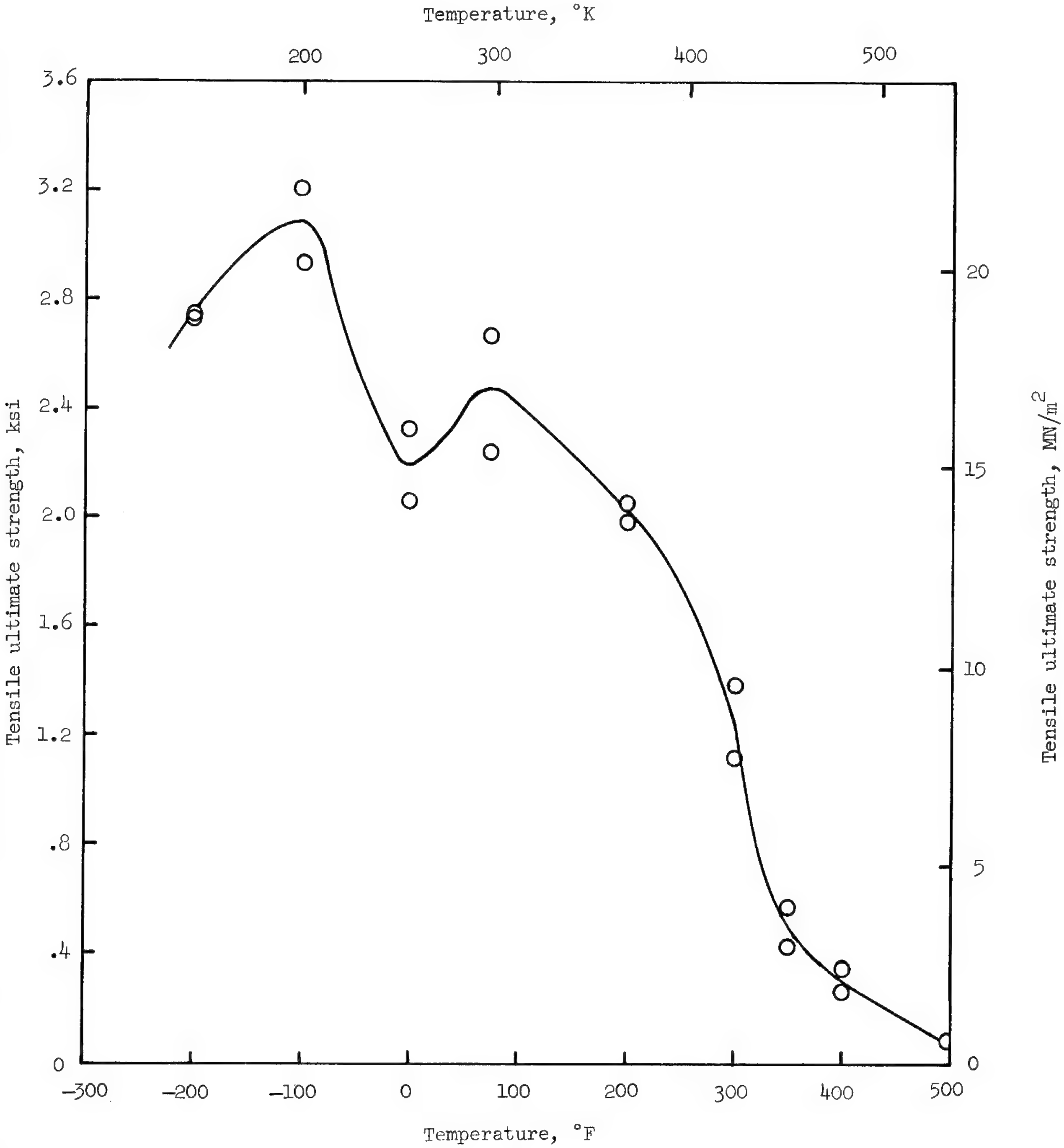


Figure 74.- Tensile ultimate strength of high-density phenolic-nylon (Melpar).

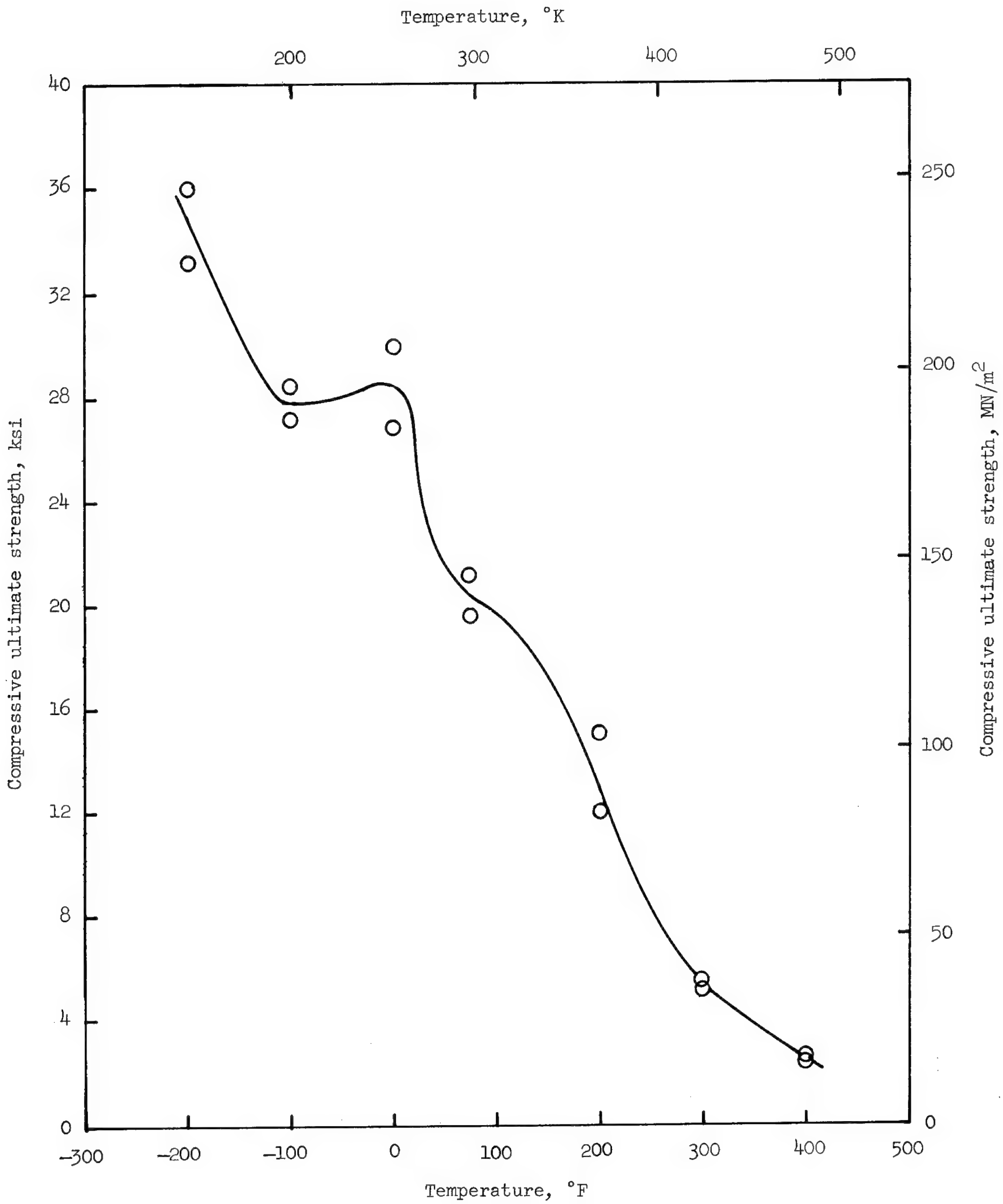


Figure 75.- Compressive ultimate strength of high-density phenolic-nylon (Melpar).

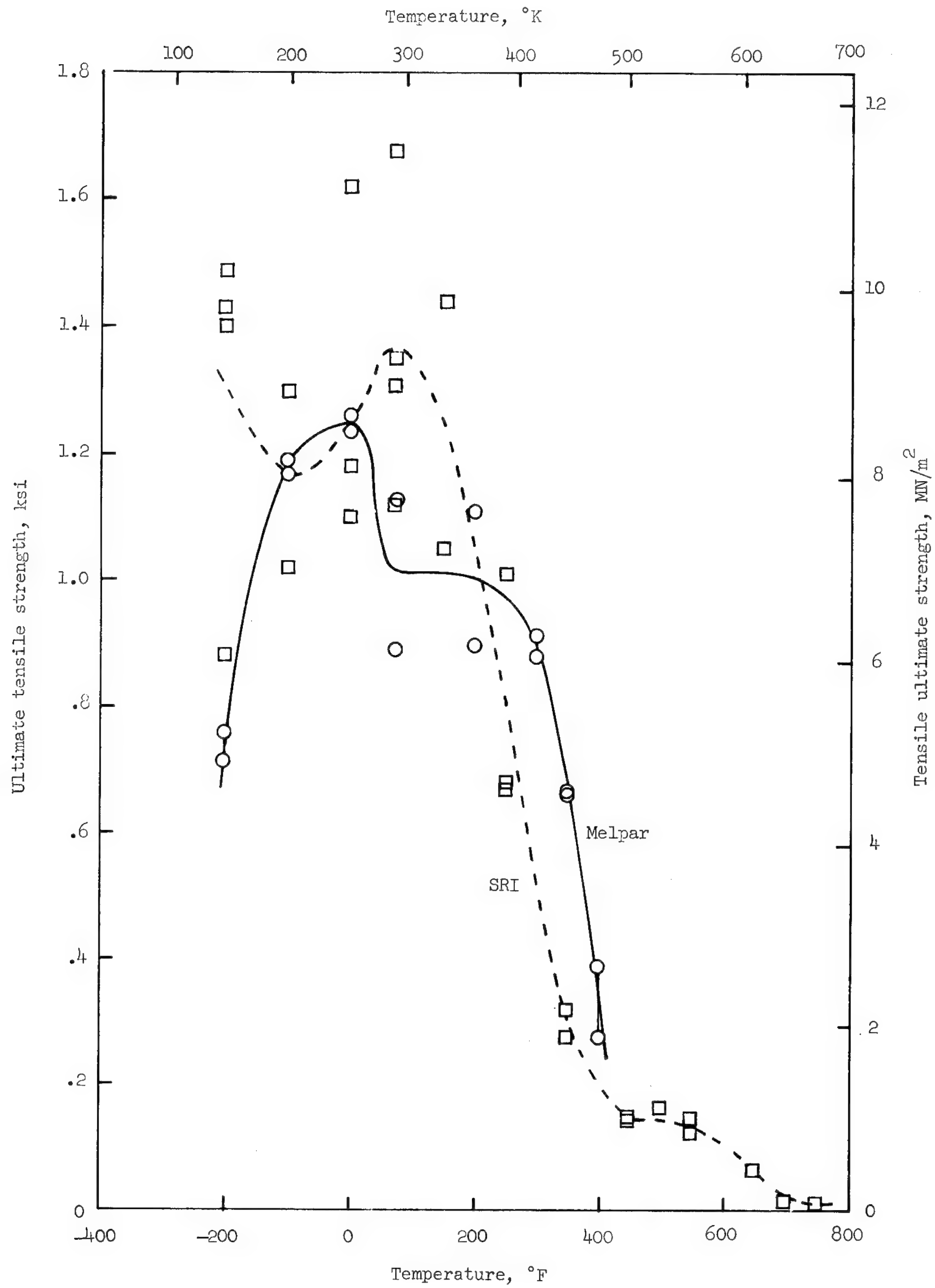


Figure 76.- Tensile ultimate strength of low-density phenolic-nylon.

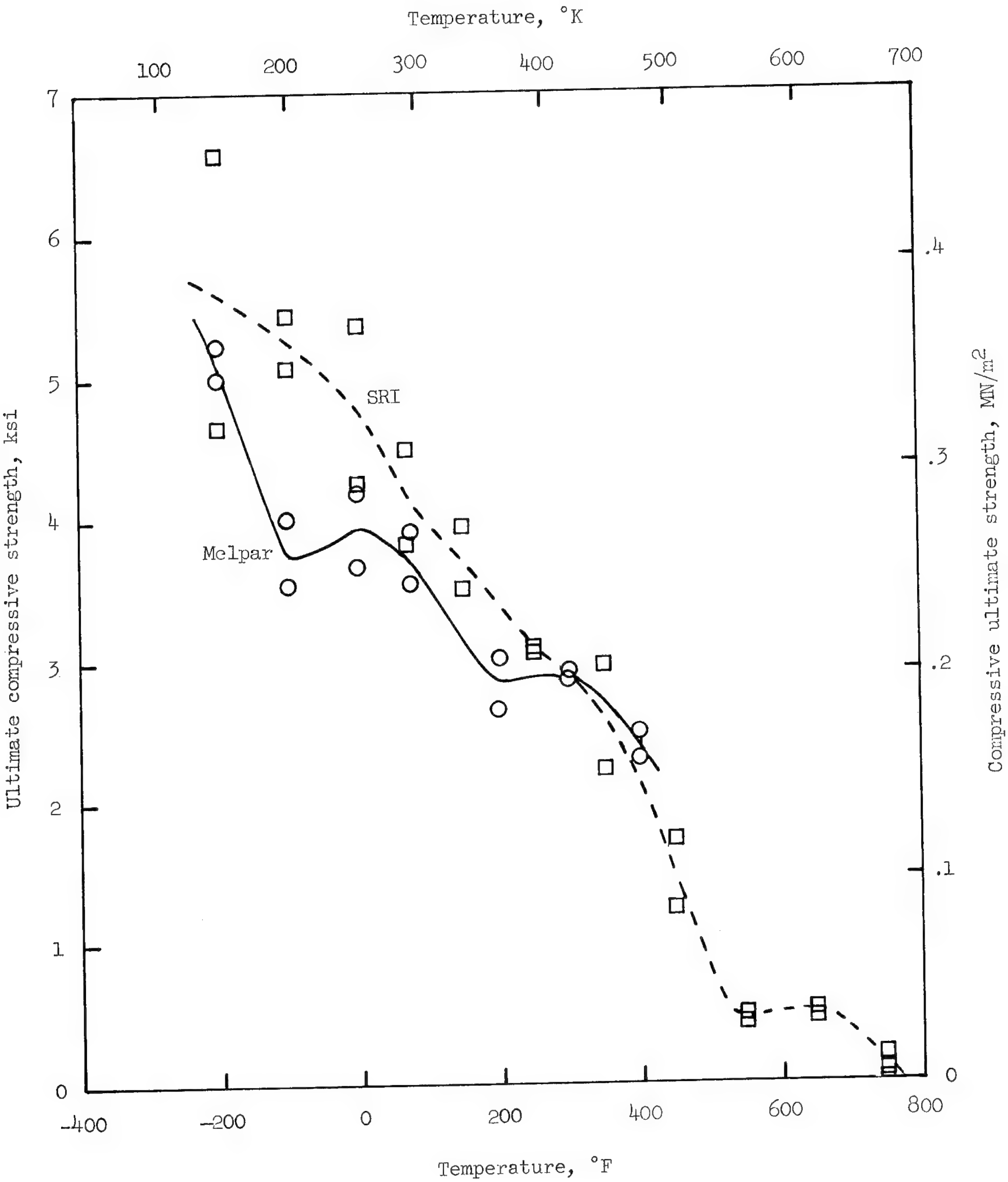


Figure 77.- Compressive ultimate strength of low-density phenolic-nylon.

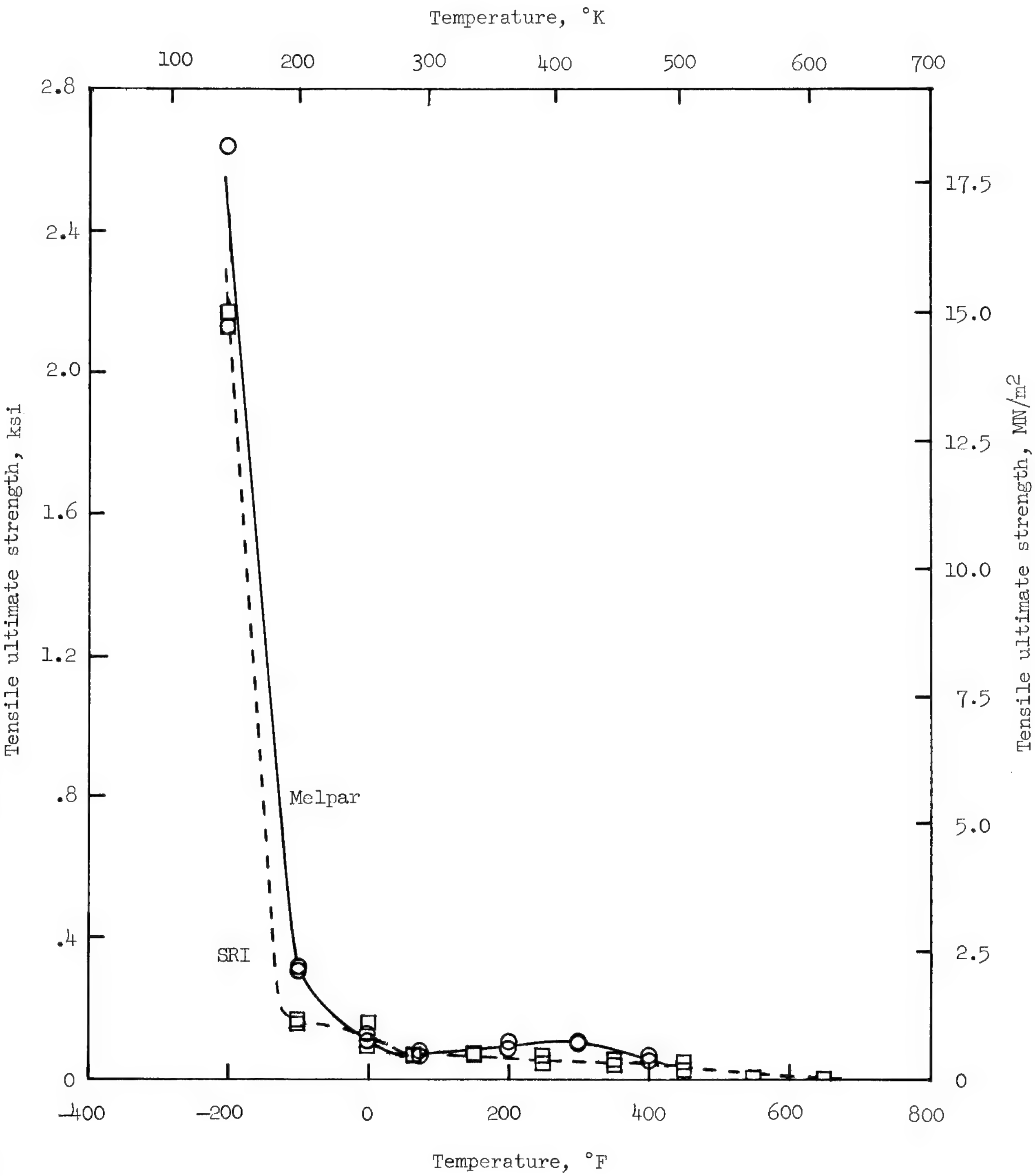


Figure 78.- Tensile ultimate strength of filled silicone resin.

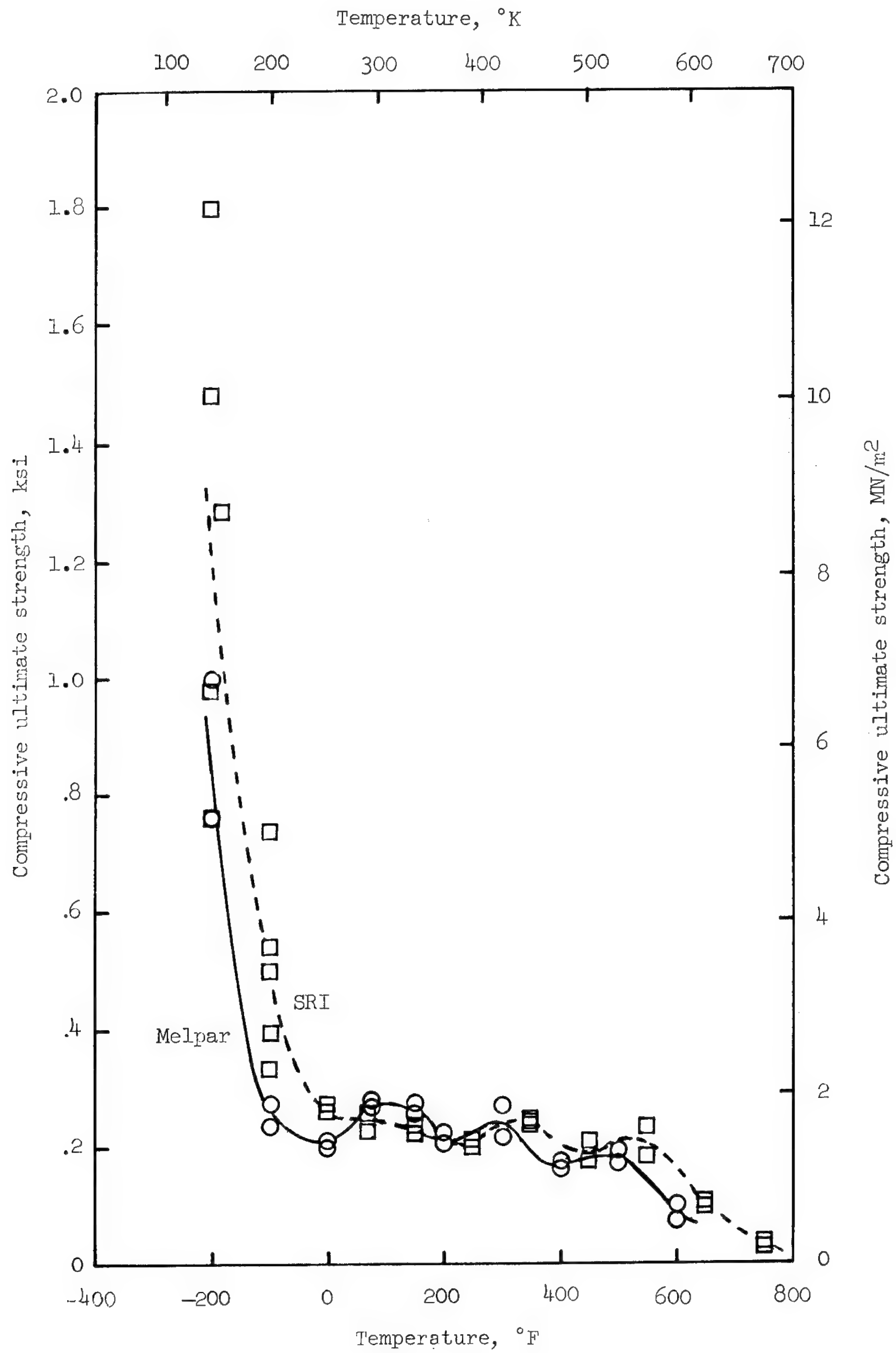


Figure 79.- Compressive ultimate strength of filled silicone resin.

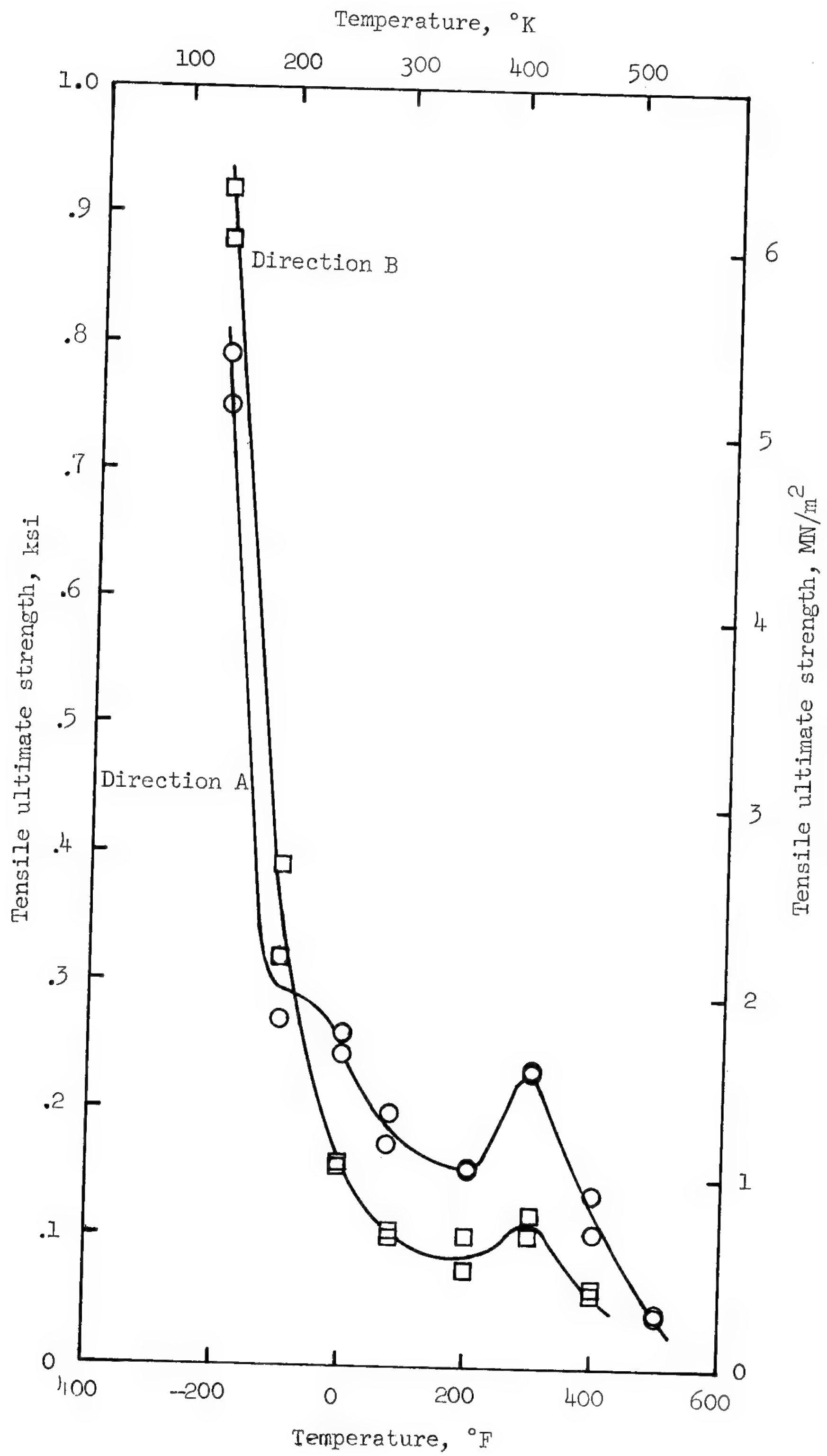


Figure 80.- Tensile ultimate strength of filled silicone resin in honeycomb (Melpar).

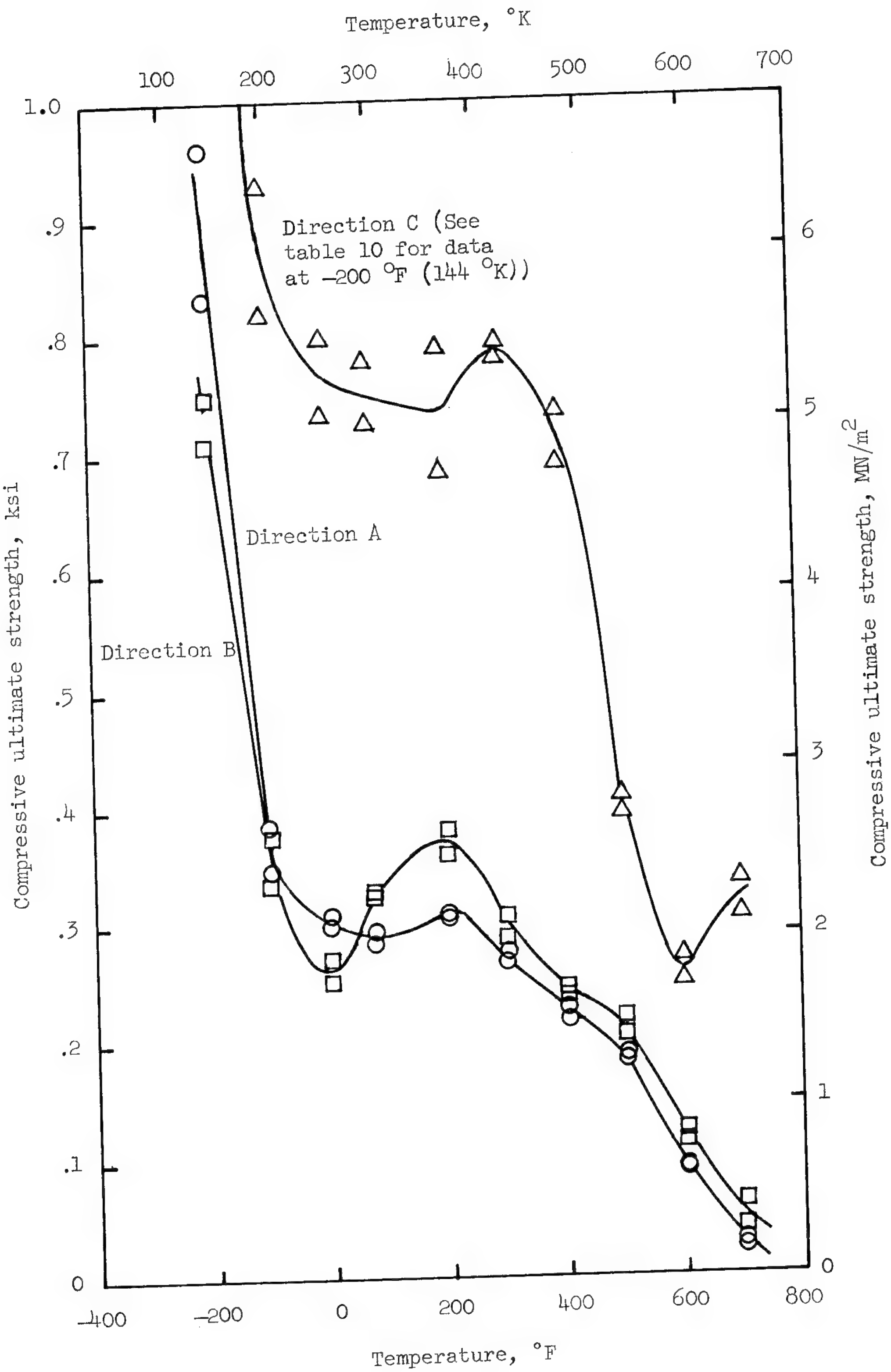


Figure 81.- Compressive ultimate strength of filled silicone resin in honeycomb (Melpar).

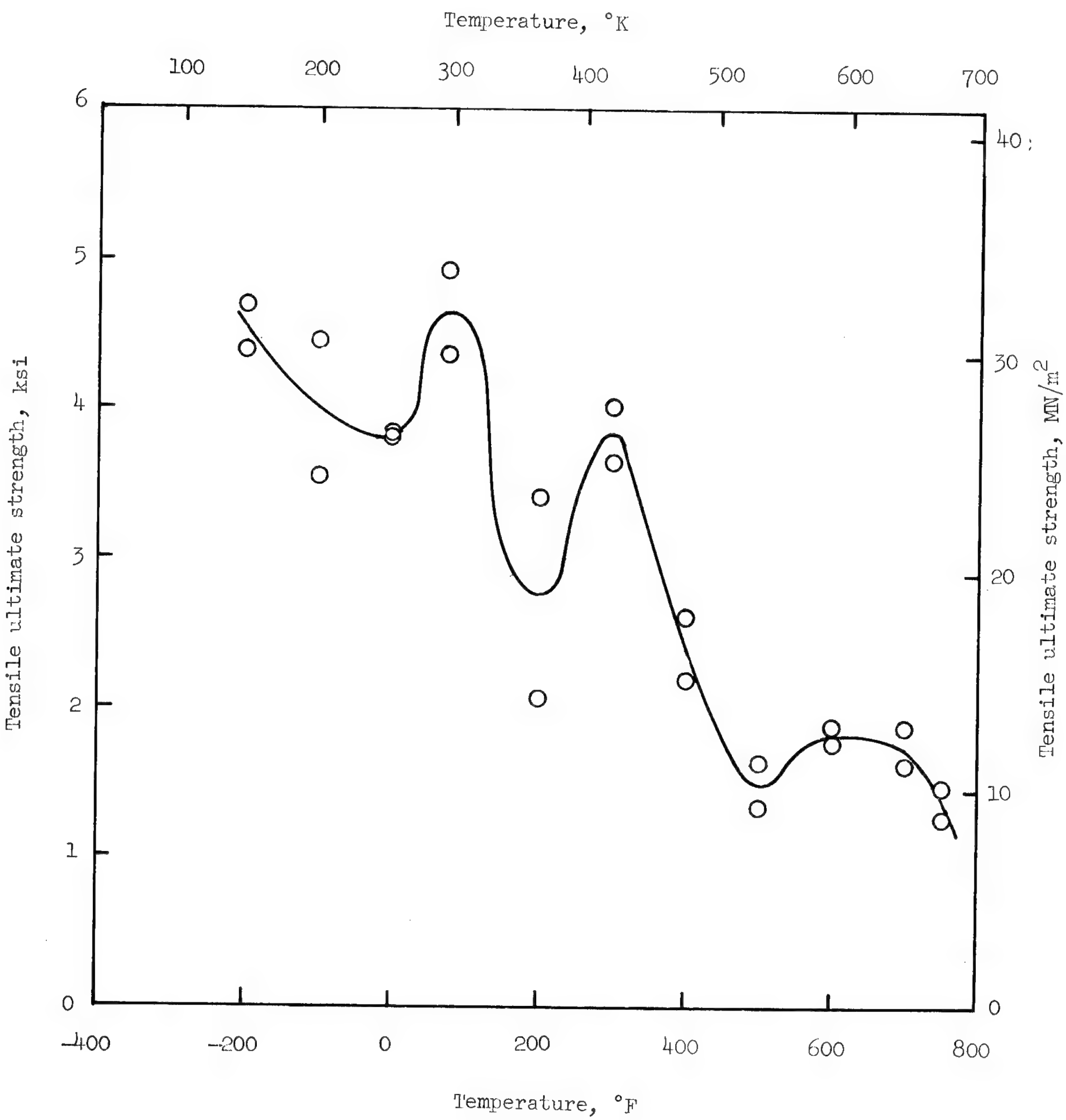


Figure 82.- Tensile ultimate strength of Narmco 4028 carbon-fiber-reinforced phenolic in tension (Melpar).

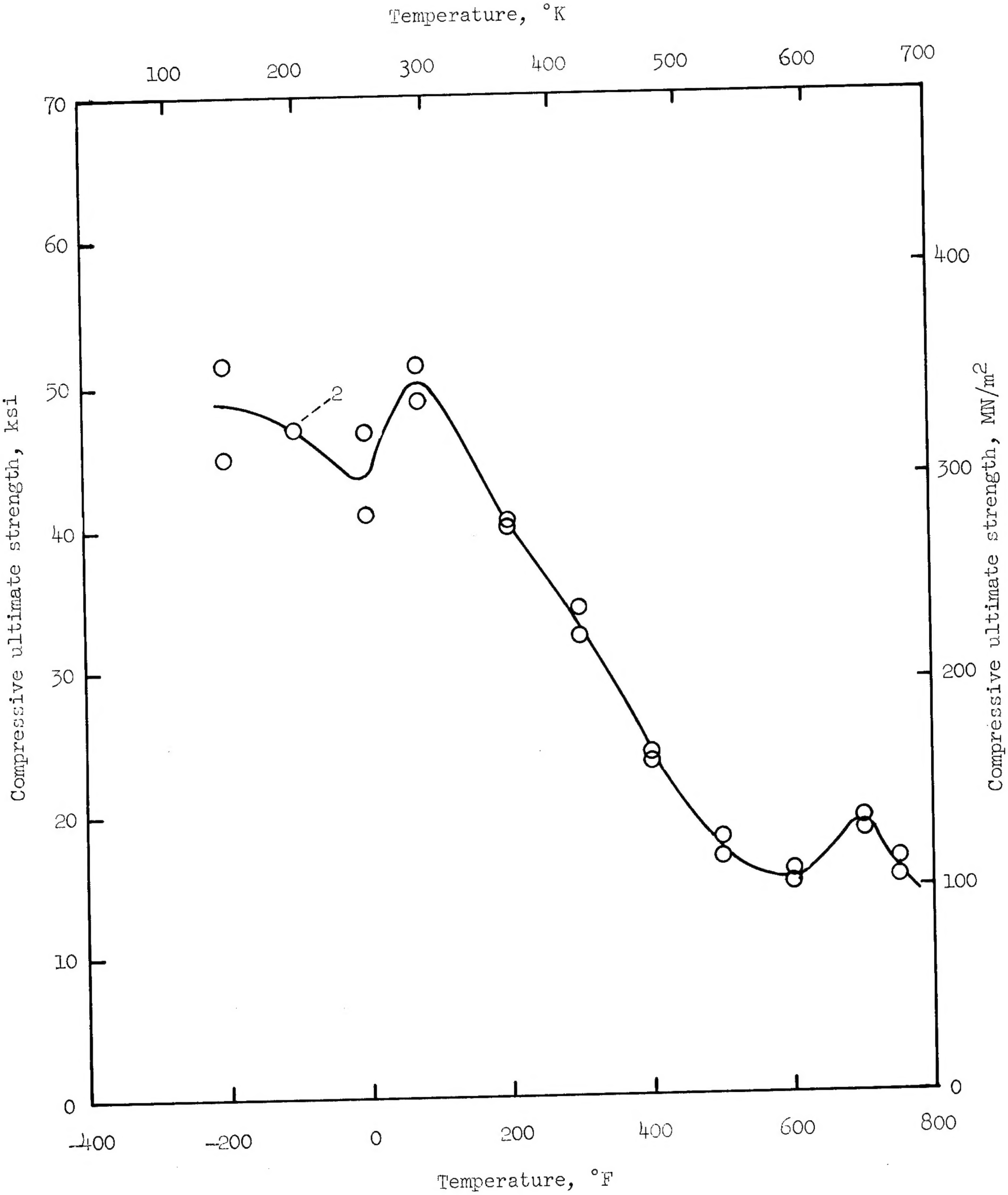


Figure 83.- Compressive ultimate strength of Narmco 4028 carbon-fiber-reinforced phenolic (Melpar).

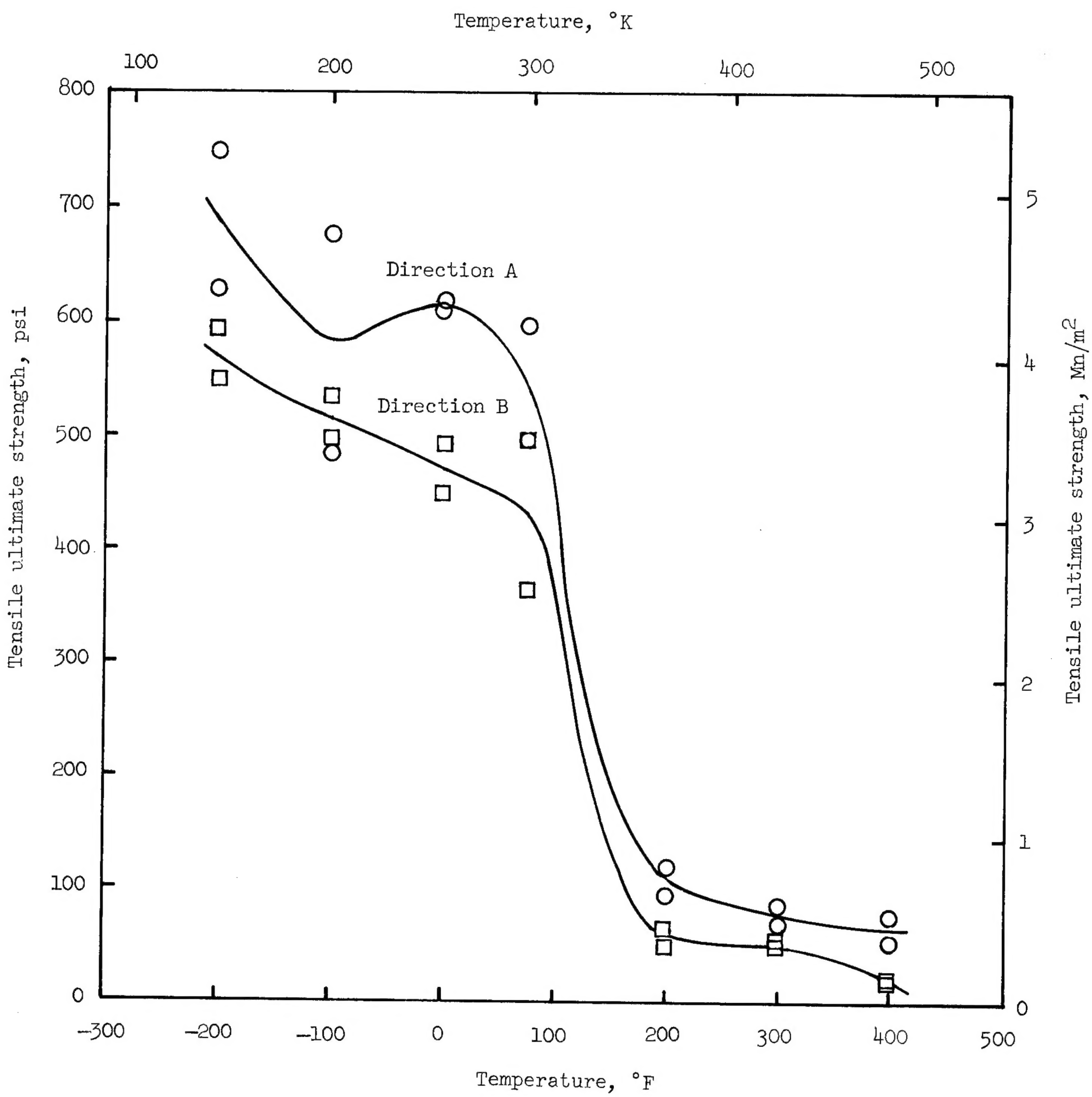


Figure 84.- Tensile ultimate strength of Avcoat 5026-39-HC G filled epoxy in honeycomb (Melpar).

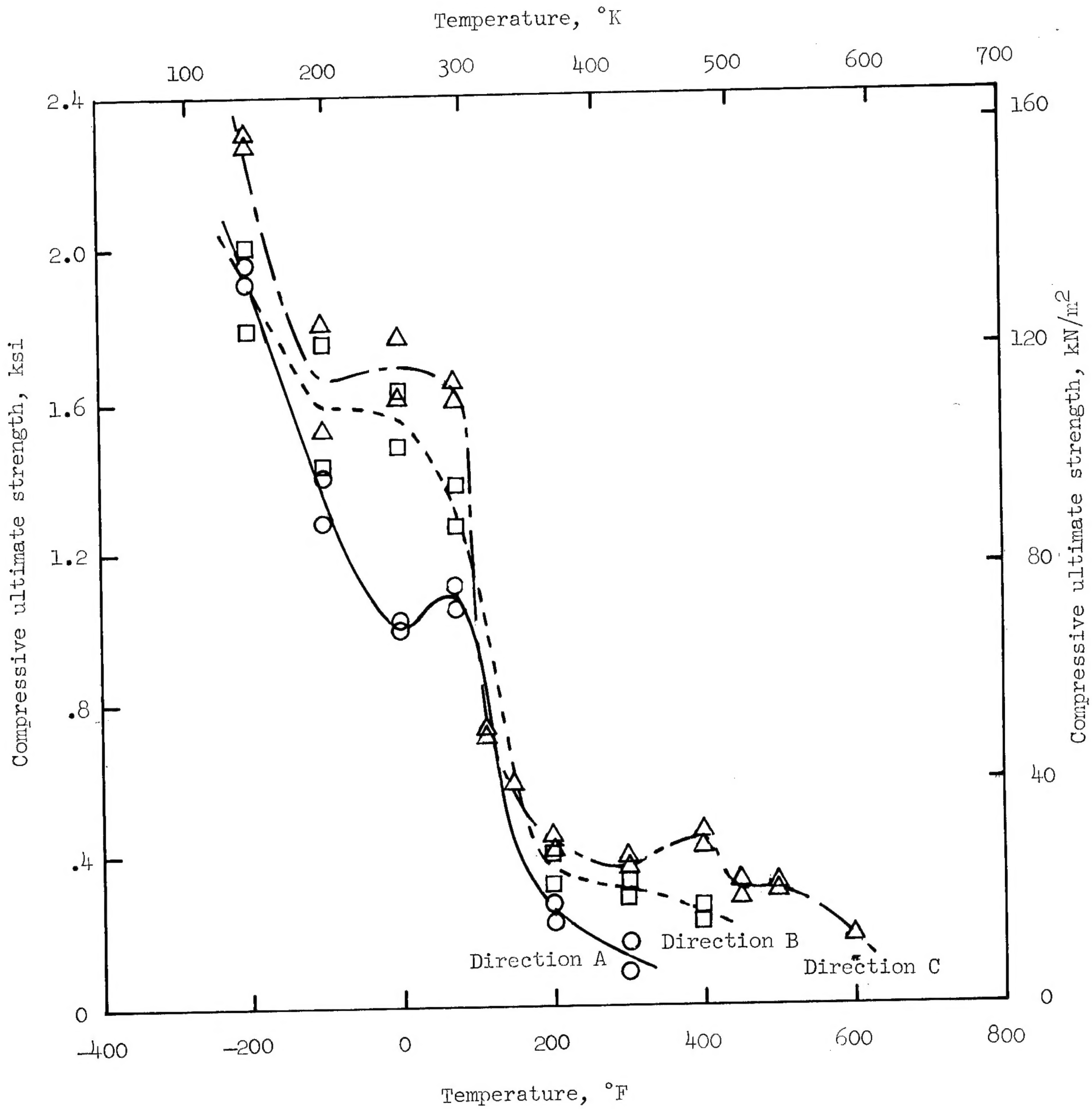


Figure 85.- Compressive ultimate strength of Avcoat 5026-39-HC G filled epoxy in honeycomb (Melpar).

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